Matters of Attention

Gaining insight in student learning in the complexity of design-based chemistry education

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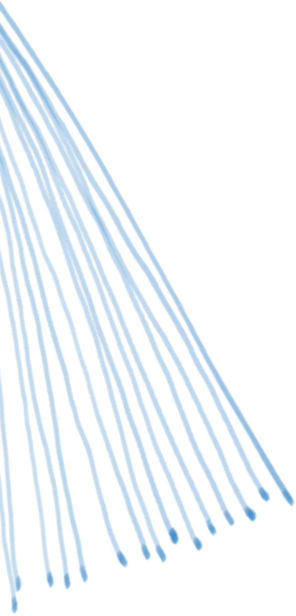

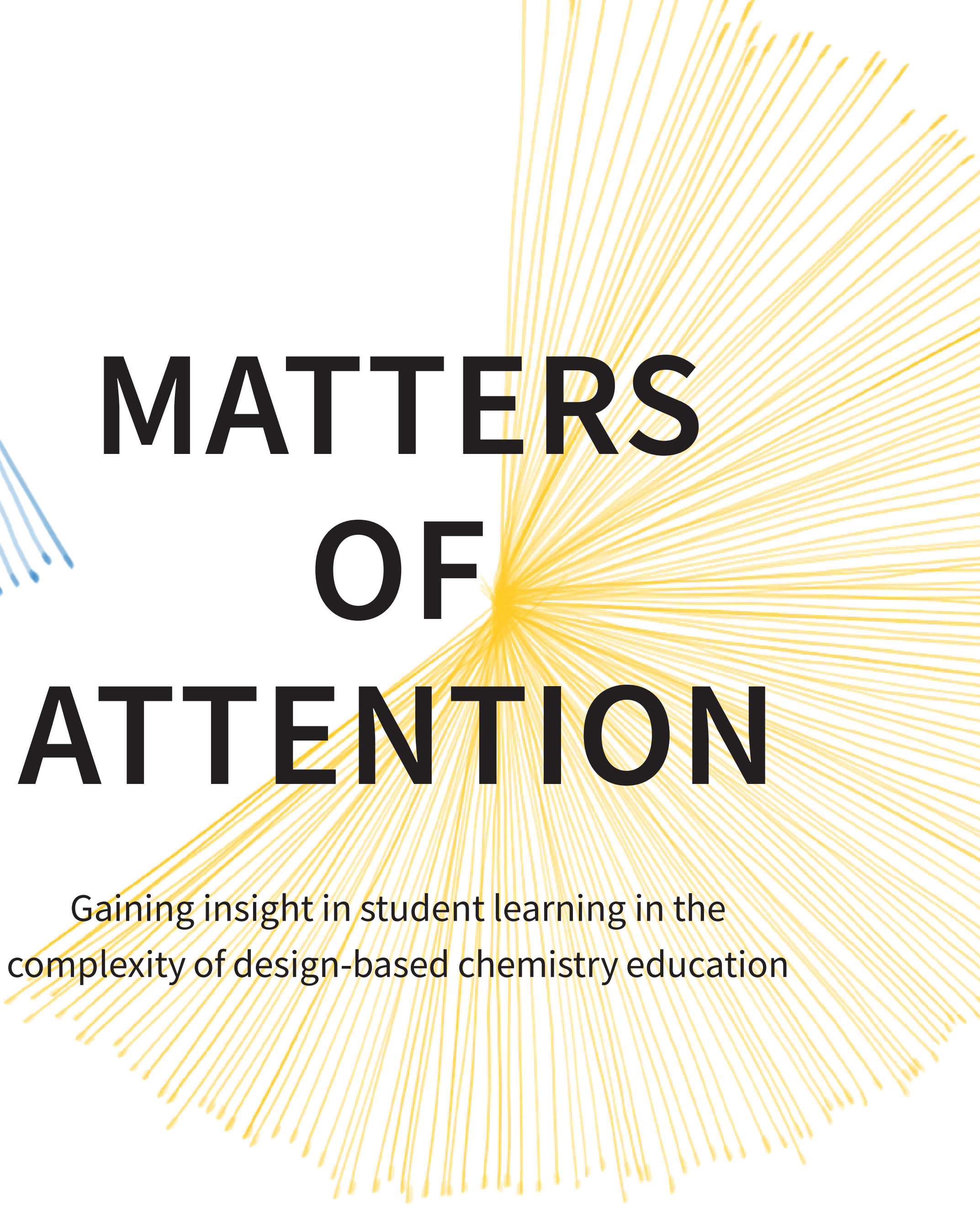

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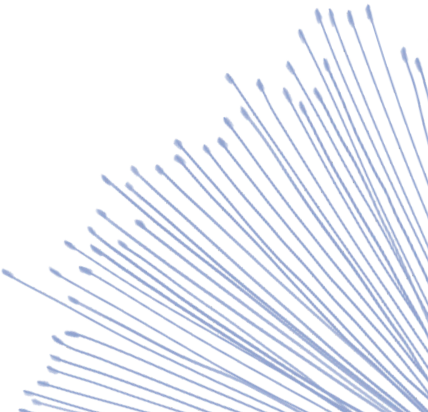
Hanna Stammes



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Gaining insight in student learning
in the complexity of
design-based chemistry education

Proefschrift

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Summary

Engaging students in design has great potential for promoting learning in science education, and design practices have been gaining emphasis in national science curricula in recent years. In the actual success of this type of instruction, teachers play a key role. Many recommended teaching practices for design-based science education hinge on *teachers' attention* to what and how students are learning as they are engaged in design. Gaining insight in student learning in the course of instruction means that teachers have the opportunity to tailor their actions to students' learning needs, and enhance student learning during a learning process. While previous research showed that teachers' attention to student learning differs between types of instruction, characterisations of teacher attention in secondary school, design-based science settings remained scarce. Attending to student learning has, nevertheless, been posited as particularly important yet complex in design-based classrooms due to design's multifaceted and open-ended nature. The reform-based character of design-based science education further contributes to this complexity, which also pertains to design-based *chemistry* education. Chemistry has, however, seldom been featured in design-based education research, despite design's central role in the chemistry discipline, and in chemistry curricula.

To contribute to the field's budding understanding of teacher attention in science education contexts, and support efforts seeking to foster teachers' expertise in design-based chemistry education, this thesis sought to investigate *what* insight in student learning chemistry teachers can gain in the complexity of design-based chemistry education, and *how*. To meet our research aim, we qualitatively studied different matters of attention, and relied on close collaboration with a community of interested, Dutch chemistry teachers.

As an initial study, we examined chemistry teachers' pedagogical ideas about design-based chemistry education (*Chapter 2*). Teachers' ideas about teaching and learning are known to influence their attention to student learning, and their adoption of curricular reforms. We conducted this study in the context of a newly-initiated professional learning community. We elicited the pedagogical ideas of the community's six teachers through semi-structured interviews, and logbooks that teachers kept while implementing a design-based chemistry project. Data analysis showed that the teachers did not see learning to design (in chemistry) as an important goal of chemistry education, instead valuing design more as a way to engage students in applying chemistry concepts, developing 'soft skills' (e.g. working independently, creativity), and applying or developing research practices. The study revealed that chemistry teachers can see design as a potentially rich and beneficial learning context for students. But, whereas design has been described as a 'natural fit' for science education, findings also suggested that the chemistry-specific nature of design is not necessarily evident

to chemistry teachers. The study furthermore demonstrated that pedagogical ideas about design-based chemistry education can vary between chemistry teachers.

In the second study, teacher attention itself became the focus of investigation (*Chapter 3*). Given the range of opportunities for student learning in design-based chemistry contexts, we were interested in examining the multidimensionality of teacher attention (i.e. the various objects of interest that grab a teacher's attention). To elicit and examine attention to student learning, we adopted a 'formative assessment' perspective, and engaged one of the community's experienced chemistry teachers in weekly reflection conversations as she implemented a design-based chemistry project. Findings demonstrated that attending to student learning in a design context can entail a teacher paying attention to disciplinary aspects of student learning (e.g. students' chemical thinking and design practices), as well as more generally-relevant aspects of learning (e.g. students' social interactions, ownership and emotions). Analysis at a finer grain size furthermore revealed changes in what the teacher attended to through time (e.g. her attention within an aspect of learning becoming more focussed). These observations also suggest that this study's adaptation of a 'midstream modulation' approach to reflection conversations offers opportunities for supporting teachers' expertise development.

Teachers' attention to student learning amidst the heat of design-based classroom activities was also investigated in this thesis (*Chapter 4*). We adopted a 'teacher noticing' perspective for this study, and zoomed in specifically on teachers' noticing of students' chemical thinking during conversations with students engaged in design planning and drawing. We collected classroom and retrospective-interview data to access the in-the-moment noticing of two chemistry teachers, and used the 'chemical thinking framework' for analysis. Findings demonstrated that one teacher may have more noticing instances, and notice student thinking concerning a wider range of chemistry concepts than another during small-group conversations. This affects the opportunities teachers have for supporting students' application and development of chemical thinking during design activities. We furthermore found that students' talk was most revealing of students' chemical thinking to the teachers, and observed that the teacher with the wider noticing scope also used other sources of information (incl. students' annotated design drawings, prototypes and gestures). Blending evidence from multiple sources may allow teachers to draw more accurate inferences about students' thinking.

In the final empirical study, we further examined the affordances of using design-authentic sources of information to characterise students' understanding of chemistry concepts in a design context (*Chapter 5*). Researchers' in-depth analyses of student data can yield suggestions for ways in which teachers can attend to student learning. We gathered data as students were engaged in design drawing and planning, and analysed students' talk within design teams, talk with the teacher participating in the teams' conversations, and annotated design drawings. We found that use of the ‘chemical thinking framework’ facilitated the characterisation of twenty five assumptions about the nature of chemical entities and processes. These assumptions were (implicitly) guiding students’ thinking during design planning and drawing, and concerned multiple chemistry concepts (incl. chemical identity, chemical control and benefits-costs-risks), and degrees of sophistication (i.e. involving more everyday or academic ideas). Comparison of the three data sources furthermore highlighted the importance of consulting and combining several design-authentic sources of information when seeking insight in students’ conceptual understanding in a design context.

Together, the four studies of this thesis provide a unique window into *what* insight in student learning teachers can gain in design-based chemistry contexts, and *how*. They demonstrate that a chemistry teacher may gain insight into multiple aspects of student learning in a design context (incl. chemical thinking, design practices, social interactions and emotion). The research also shows that a teacher’s objects of attention in a design-based chemistry context can change through time, and that the type of insights gained can differ between chemistry teachers. This variety creates different opportunities for teachers to support student learning in a design-based classroom. To gain insight in student learning in a design context, the research suggests that both in-class and out-of-class, reflective settings offer affordances for teachers. The studies additionally reveal the importance of using students’ talk in addition to other sources of information (incl. annotated design drawings), and of paying attention to students’ everyday and implicit chemistry ideas when pursuing insight in students’ chemical thinking in design contexts. Furthermore, drawing on multiple rather than a single perspective on teacher attention seems to be an effective strategy to advance understanding of teachers’ attention to student learning in science education.

While this research’s qualitative and small-scale setup proved valuable for exploring attention to student learning in design-based chemistry education, follow-up research is desirable. Studies could examine the multidimensional attention and evidence-use of more chemistry teachers, and in other design-based settings. Also, what may be characterised as productive attention – in other words, what attention matters – is still a topic of debate in educational literature. To come to definitions of productive attention in design-based chemistry settings, future research should seek to connect teacher attention to student learning outcomes. Subsequent research into the relation between attention and other elements of teacher expertise (incl. cognitions and classroom practice), as well as research into the development of expertise is furthermore essential for those seeking to support (prospective) chemistry teachers’ implementation of design-based chemistry education.

This research yields suggestions for teachers and teacher educators. It draws focus to the importance of gaining insight in student learning while also describing what aspects of learning may be observed in design-based chemistry classrooms. A framework untangling possible objects of attention is presented (see *Chapter 6*), which could serve as a tool for making sense of student learning in a design context and facilitating discussions about what attention matters. This research also highlights the value of teachers eliciting students' chemical thinking through multiple, design-authentic sources of information. When interpreting such information, adopting an inferential stance (i.e. seeking sensibility in students' thinking rather than evaluating thinking against canonical chemistry), could be particularly revealing of students' chemical thinking in a design context. The research furthermore suggests that teacher educators may want to draw on chemistry teachers' (diverse) motivations for bringing design into their classroom as a resource for professional development, and address design not just from a general science or engineering perspective but from a chemical one as well. Regarding supporting development of attention, the research points to the potential of engaging teachers in reflective dialogue revolving around information on student learning. Because of the mediating role of attention in teachers' expertise, such activities might also help build teachers' cognitions and classroom practice regarding design-based chemistry education.

Samenvatting

Ontwerpen heeft de afgelopen jaren een prominentere plek gekregen in de curricula van bètavakken in verschillende landen. Leerlingen laten ontwerpen heeft immers grote potentie voor het bevorderen van leren in bètaonderwijs. In het daadwerkelijke succes van dit type onderwijs blijken docenten een sleutelrol te hebben. Veel van de docentpraktijken die worden aanbevolen voor succesvol ontwerpgericht bètaonderwijs hangen af van de *aandacht* die docenten hebben voor wat en hoe leerlingen leren terwijl ze ontwerpen. Inzicht krijgen in het leren van leerlingen betekent dat docenten de mogelijkheid hebben om hun acties af te stemmen op de leerbehoeftes van leerlingen en zo hun leren te bevorderen. Hoewel eerder onderzoek heeft laten zien dat de aandacht van docenten voor het leren van leerlingen verschilt tussen soorten bètaonderwijs, zijn typeringen van die aandacht in ontwerpgerichte bètacontexten in het voortgezet onderwijs schaars. Aandacht besteden aan leren tijdens ontwerpgericht onderwijs lijkt echter zowel bijzonder belangrijk als complex te zijn vanwege de veelzijdigheid en openheid van ontwerpopdrachten. Het vernieuwende karakter van ontwerpgericht bètaonderwijs draagt verder bij aan deze complexiteit, ook als het gaat om ontwerpgericht scheikundeonderwijs. In eerder onderzoek is het schoolvak scheikunde echter zelden voor het voetlicht gebracht. Dit terwijl ontwerpen wel een centrale rol heeft in zowel de discipline scheikunde als in scheikundecurricula.

Om bij te dragen aan de kennis over docentaandacht in bètacontexten en aan initiatieven ter bevordering van de expertise van docenten op het gebied van ontwerpgericht scheikundeonderwijs, had deze thesis tot doel om te onderzoeken *wat voor* inzichten in leren scheikundedocenten kunnen opdoen in de complexiteit van ontwerpgericht scheikundeonderwijs en *hoe* ze dergelijke inzichten kunnen opdoen. Hiertoe bestudeerden we kwalitatief verschillende kwesties rond docentaandacht en werkten we nauw samen met een leergemeenschap van geïnteresseerde, Nederlandse scheikundedocenten.

Als eerste bestudeerden we de didactische ideeën van scheikundedocenten over ontwerpgericht scheikundeonderwijs (*Hoofdstuk 2*). De ideeën van docenten over onderwijzen en leren beïnvloeden hun aandacht voor het leren van leerlingen en hun implementatie van curriculumvernieuwingen. We voerden de studie uit in de context van een nieuw-opgezette professionele leergemeenschap waartoe zes scheikundedocenten behoorden. We ontlokten de didactische ideeën van deze docenten door semigestructureerde interviews af te nemen en door docenten te vragen logboeken bij te houden gedurende de uitvoering van een ontwerpgericht scheikundeproject. Data-analyse liet zien dat de docenten leren ontwerpen (in scheikunde) niet zagen als een belangrijk doel van scheikundeonderwijs. Ze waardeerden ontwerpen meer als een manier om leerlingen scheikundeconcepten te laten toepassen, ‘zachte vaardigheden’ te laten ontwikkelen (bijv. zelfstandig werken, creativiteit) en onderzoeksvaardigheden te laten toepassen of ontwikkelen. De studie onthulde dat scheikundedocenten ontwerpen kunnen zien als een potentieel rijke en kansrijke leeromgeving voor leerlingen. Maar, daar waar ontwerpen weleens is beschreven als een 'natuurlijke fit' voor bètaonderwijs, suggereerden onze resultaten dat het scheikunde-specifieke karakter van ontwerpen niet noodzakelijkerwijs evident is voor scheikundedocenten. De studie toonde daarnaast aan dat scheikundedocenten verschillende didactische ideeën over ontwerpgericht bètaonderwijs kunnen hebben.

In de tweede studie werd docentaandacht zelf het onderwerp van onderzoek (*Hoofdstuk 3*). Vanwege het scala aan mogelijkheden voor leren in ontwerpgericht scheikundeonderwijs wilden we het multidimensionale karakter van docentaandacht in deze context in kaart brengen (d.w.z. de verscheidene onderwerpen die de aandacht van een docent vangen). Om deze aandacht te kunnen bestuderen gebruikten we het perspectief van 'formatieve evaluatie' en betrokken we een ervaren scheikundedocent uit de leergemeenschap in wekelijkse reflectiegesprekken terwijl ze een ontwerpgericht scheikundeproject uitvoerde. Resultaten toonden aan dat aandacht besteden aan leren in een ontwerpcontext zowel kan betekenen dat een docent let op disciplinaire aspecten van leren (bijv. het scheikundig denken en de ontwerppraktijken van leerlingen) als op meer algemeen-relevante aspecten van leren (bijv. sociale interacties, eigenaarschap en emoties). Analyses op een gedetailleerder niveau onthulden daarnaast veranderingen in docentaandacht door de tijd heen (bijv. aandacht die binnen een aspect van leren meer gefocust werd). Deze observaties suggereren ook dat de voor de reflectiegesprekken gebruikte 'midstream modulation' aanpak kansen biedt voor het ondersteunen van de ontwikkeling van docentexpertise.

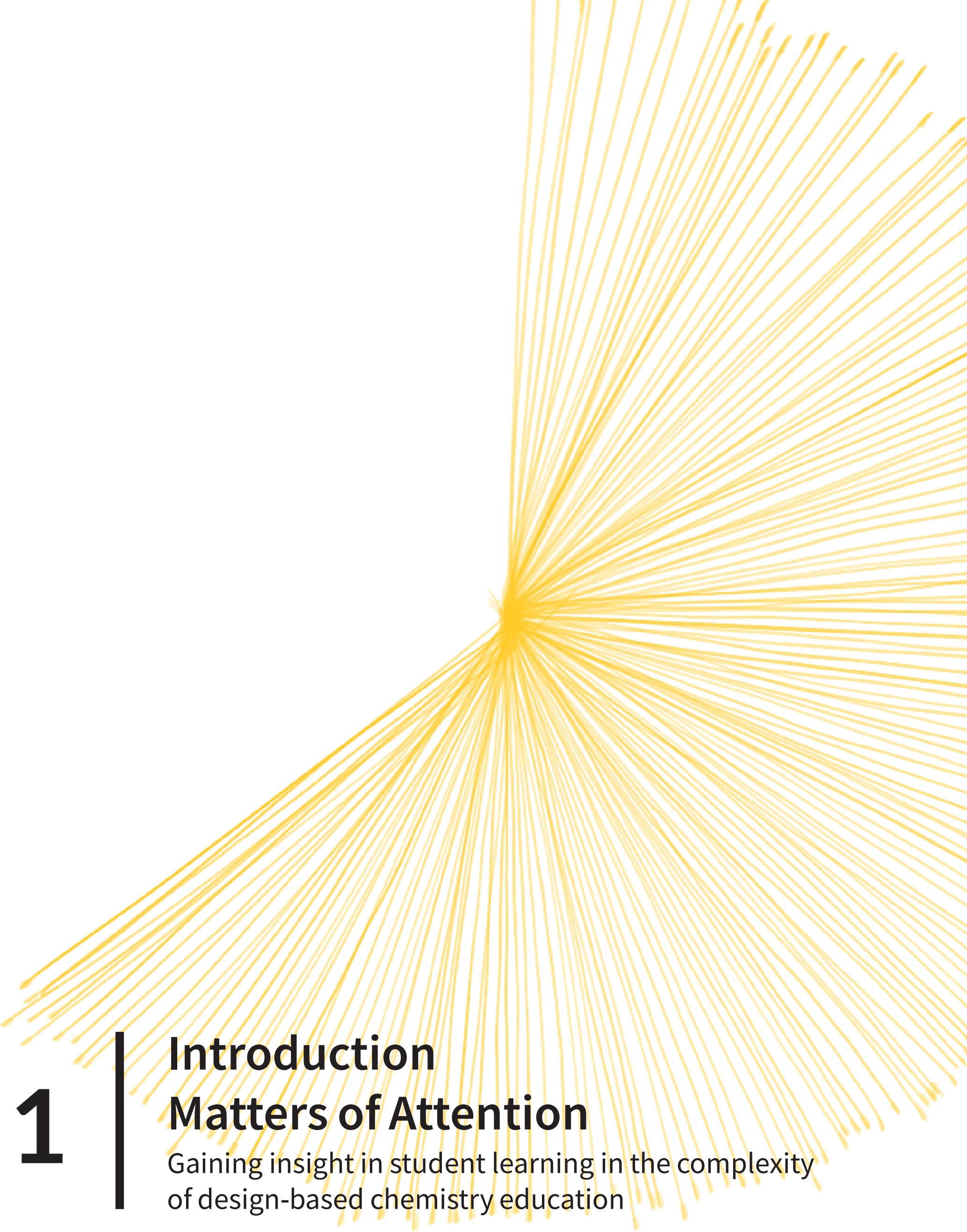
De aandacht van docenten voor het leren van hun leerlingen te midden van ontwerpgerichte lesactiviteiten werd ook bestudeerd in deze thesis (*Hoofdstuk 4*). Voor deze studie namen we een opmerkzaamheidsperspectief aan ('teacher noticing') en zoomden we specifiek in op het opmerken van scheikundig denken door docenten terwijl leerlingen ontwerpideeën bedachten en tekenden. Om toegang te krijgen tot de opmerkzaamheid van twee scheikundedocenten verzamelden we data in de klas en namen we retrospectieve interviews af. We gebruikten het 'scheikundig-denken-raamwerk' voor de data-analyse. Resultaten toonden aan dat de ene docent tijdens gesprekjes met ontwerpteams meer momenten van opmerkzaamheid kan hebben en tevens leerlingdenken rond een grotere variëteit aan scheikundige concepten kan opmerken dan een andere docent. Dit beïnvloedt de mogelijkheden die docenten hebben om leerlingen te helpen in het toepassen en ontwikkelen van scheikundig denken tijdens ontwerpactiviteiten. We ontdekten in deze studie ook dat wat leerlingen zeiden voor docenten het meest onthulde over hun scheikundig denken en observeerden dat de docent met de breedste opmerkzaamheid ook andere informatiebronnen gebruikte (waaronder de geannoteerde ontwerptekeningen van leerlingen, hun prototypes en gebaren). Het versmelten van informatie uit meerdere bronnen stelt docenten mogelijk beter in staat om denken van leerlingen nauwkeurig af te leiden.

In de laatste empirische studie zijn de mogelijkheden van het gebruik van ontwerpauthentieke informatiebronnen voor de karakterisering van begrip over scheikundige concepten nader bestudeerd (*Hoofdstuk 5*). Grondige analyses van leerlinginformatie door onderzoekers kan ideeën opleveren voor manieren waarop docenten aandacht zouden kunnen besteden aan het leren van leerlingen. We verzamelden data voor deze studie terwijl leerlingen ontwerpideeën bedachten en tekenden en analyseerden wat leerlingen zeiden binnen hun ontwerpteams, wat ze zeiden wanneer de docent deelnam aan de conversatie als ook hun geannoteerde ontwerptekeningen. We ontdekten dat toepassing van het 'scheikundig-denken-raamwerk' de karakterisering van vijfentwintig aannames over de aard van scheikundige entiteiten en processen mogelijk maakte. Deze aannames stuurden (impliciet) het denken van leerlingen tijdens het ontwerpen. De aannames hadden betrekking op meerdere scheikundige concepten (waaronder chemische identiteit, controle en 'kosten-baten-risico's') en niveaus van complexiteit (meer alledaagse of wetenschappelijke ideeën). Een vergelijking van de drie databronnen onderstreepte daarnaast het belang van het consulteren en combineren van meerdere ontwerpauthentieke informatiebronnen om inzicht te krijgen in het conceptuele begrip van leerlingen in een ontwerpcontext.

Gezamenlijk bieden de vier studies een uniek inkijkje in wat voor inzicht in het leren van leerlingen docenten kunnen opdoen in ontwerpgerichte scheikundecontexten en hoe. Het onderzoek toont aan dat een scheikundedocent in een ontwerpcontext inzicht zou kunnen krijgen in meerdere aspecten van leren (zoals scheikundig denken, ontwerppraktijken, sociale interacties en emoties). De studies laten ook zien dat de onderwerpen die de aandacht van een docent trekken door de tijd heen kunnen veranderen en dat opgedane inzichten kunnen verschillen tussen docenten. Deze variëteit creëert verschillende mogelijkheden voor docenten om het leren van leerlingen in een ontwerpgerichte les te ondersteunen. Het onderzoek suggereert verder dat zowel situaties in de klas als reflectieve situaties buiten de klas kansen bieden voor docenten om inzicht te krijgen in het leren van leerlingen in een ontwerpcontext. Om inzicht te krijgen in het scheikundig denken van leerlingen in een ontwerpcontext onthullen de studies daarnaast het belang van gebruiken wat leerlingen zeggen in combinatie met andere informatiebronnen (zoals geannoteerde ontwerptekeningen) en het belang van letten op alledaagse en impliciete scheikundige ideeën van leerlingen. Daarnaast lijkt het toepassen van meerdere perspectieven op docentaandacht in plaats van een enkel perspectief een effectieve strategie om onze kennis over aandacht voor leren in bètaonderwijs te vergroten.

Hoewel het kwalitatieve en kleinschalige karakter van dit onderzoek succesvol bleek te zijn om aandacht voor leren in de context van ontwerpgericht scheikundeonderwijs te verkennen, is vervolgonderzoek wenselijk. Vervolgstudies zouden de multidimensionale aandacht en het informatiegebruik van meer scheikundedocenten in kaart kunnen brengen als ook docentaandacht in andere ontwerpcontexten. Bovendien, wat kan worden gekarakteriseerd als productieve aandacht is nog steeds onderwerp van debat in de onderwijsliteratuur. Om tot definities van productieve aandacht in ontwerpgerichte scheikundecontexten te komen dient de aandacht van docenten voor leren te worden verbonden met leeropbrengsten bij leerlingen. Verder onderzoek naar de relatie tussen aandacht en andere elementen van docentexpertise (waaronder kennis en lespraktijk) en naar de ontwikkeling van docentexpertise is daarnaast nodig om de ontwikkeling van de expertise van (beginnende) docenten in ontwerpgericht scheikundeonderwijs beter te kunnen faciliteren.

Dit onderzoek levert aanbevelingen op voor docenten en lerarenopleiders. Het zet de schijnwerper op het belang van inzicht krijgen in het leren van leerlingen en beschrijft tevens wat voor aspecten van leren geobserveerd zouden kunnen worden in ontwerpgericht scheikundeonderwijs. Een raamwerk dat mogelijke onderwerpen van aandacht ontrafelt wordt gepresenteerd (zie *Hoofdstuk 6*). Dit raamwerk zou als tool kunnen dienen om leren in een ontwerpcontext te interpreteren en gesprekken over productieve aandacht te faciliteren. Dit onderzoek benadrukt verder dat het ontlokken van scheikundig denken middels meerdere, ontwerp-authentieke informatiebronnen docenten inzicht zou kunnen bieden in leren. Voor de interpretatie van dergelijke informatie lijkt het in ontwerpcontexten waardevol te zijn om een ‘inferential stance’ in te nemen (d.w.z. zoekend naar de logica in het denken van leerlingen i.p.v. denken afzetten tegen een scheikundecanon). Lerarenopleiders zouden de (verschillende) motivaties van docenten om ontwerpen hun scheikundeonderwijs te integreren kunnen aanwenden ten behoeve van professionaliseringsactiviteiten. Daarbij lijkt het belangrijk dat ontwerpen niet enkel vanuit een generiek natuurwetenschappelijk of technisch perspectief bekeken wordt, maar ook vanuit een scheikundig perspectief. Ter ondersteuning van de ontwikkeling van aandacht voor leren wijst dit onderzoek op de mogelijkheid om docenten te betrekken in reflectieve gesprekken rondom bronnen van informatie over het leren van leerlingen. Gezien de centrale rol die aandacht voor leren speelt in docentexpertise, zouden zulke activiteiten ook kunnen helpen bij het ontwikkelen van de kennis en praktijken van docenten rond ontwerpgericht scheikundeonderwijs.



1

Introduction

Matters of Attention

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1.1 Introduction

Engineers and scientists regularly engage in design practices, meaning the integration of various skills and ways of thinking used to identify and solve design challenges (National Research Council [NRC], 2009). Using design practices like identifying constraints, generating possible solutions, testing ideas and balancing trade-offs, they develop products and processes for preventing and treating diseases, combating climate change, and ensuring food and water quality and availability. But, design is not just reserved for professionals. As Christine Cunningham, educational researcher, notes: ‘Children are born engineers - they are fascinated with designing their own creations, with taking things apart, and with figuring out how things work’ (p. 11, 2009). Educational research from the last decades has shown that drawing on this interest for design yields important benefits for science education. For example, engaging students in design challenges can help students with diverse cultural and socio-economic backgrounds, and diverse academic and language proficiencies apply and develop understanding of science concepts (e.g. Apedoe et al., 2008; Mehalik et al., 2008; Wilson-Lopez et al., 2016). Design-based approaches to science education have furthermore been found to support students’ development of design and research practices (Fan & Yu, 2017; Kolodner et al., 2003). Others have highlighted, for instance, design’s power for enhancing students’ real-world problem solving skills (Fortus et al., 2005), collaborative and metacognitive skills (Kolodner et al., 2003), or interest in engineering careers (Reynolds et al., 2009). Considering these findings and design’s key role in our society it is unsurprising that design practices have been gaining emphasis in national science curricula (incl. Board of Tests and Examinations [CvTE], 2014; NRC, 2012).

While design has potential for promoting learning in science education, teachers play a key role in its success. In their seminal work, Janet Kolodner and colleagues (2003) draw on their elaborate research to describe how teachers can make design-based science classrooms thrive. Within their set of recommended practices they note that teachers need to ‘help students […] compare and contrast their ideas, and identify what they need to learn to move forward’, ‘provide help as needed’, ‘assess the progress of individuals’ and ‘foster a collaborative classroom culture in which students want to be engaged in deep learning’ (Kolodner et al., 2003). Another field of educational research tells us that such teaching practices hinge on *teachers’ attention* to what and how students are learning during design-based science education. Gaining insight in student learning in the course of instruction means that teachers have the opportunity to tailor their actions to students’ learning needs, and enhance student learning during a learning process (e.g. Black & Wiliam, 2009; Cowie et al., 2018; Hammer et al., 2012). In other words, closely attending to student learning enables teachers to enact practices like ‘providing help as needed’, and support student learning in design-based science classrooms. Characterisations of teachers’ attention to student learning in design-based science settings are, however, still scarce. Even though teachers’ attention to student learning has been found to vary between types of science instruction (Russ & Luna, 2013).

By studying matters of attention, this thesis aims to expand our understanding of what insight in student learning teachers can gain in design-based chemistry education, and how. Capturing and portraying teachers' attention to student learning in design-based science contexts could help explain what enables or constrains teachers, like those in Kolodner's research, to enact recommended design-based teaching practices. In addition to advancing our theoretical understanding, such investigations can facilitate efforts seeking to support prospective or in-service teachers' (developing) attention. This is a pressing matter, as attention to student learning is increasingly getting recognised by educational researchers and teacher educators as an important facet of science teachers' expertise (e.g. Barnhart & van Es, 2015; Chan et al., 2020; Levin et al., 2009). Moreover, attending to student learning may be particularly difficult for teachers in design-based contexts (Watkins et al., 2018).

In the following paragraphs, we go into teacher attention in more detail, and address the complexity of design-based science and chemistry education. Chemistry education is the science subject of focus in this research. While design is a key practice in chemistry (Talanquer, 2013), and integral part of several secondary school chemistry curricula (CvTE, 2014; NRC, 2012), chemistry is seldom featured in design-based education research.

1.2 Attention to student learning

Teachers' attention to student learning lies at the core of multiple notions currently shaping the educational landscape (also see Russ, 2018). These include formative assessment (Black & Wiliam, 2009; Coffey et al., 2011), teacher noticing (M. Sherin et al., 2011a; Jacobs et al., 2011), and responsive teaching (Hammer et al., 2012). These different, yet interrelated educational notions offer complementing perspectives on what it means to attend to student learning. Formative assessment research, for example, has highlighted the importance of teachers eliciting evidence of student learning (Black & Wiliam, 2009), so that student learning may be perceived and interpreted. Certain views on formative assessment overlook, however, the full scope of student information that can be valuable to teachers' practice (Shapiro & Wardrip, 2019), or the specific objects of teachers' attention (Coffey et al., 2011). A construct like teacher noticing, on the other hand, revolves around teachers' attention to student learning amidst the wealth of sensory information that arises through classroom interactions (M. Sherin et al., 2011a). This notion furthermore acknowledges teachers' objects of attention, such as those involving disciplinary aspects of student learning (Erickson, 2011; Jacobs et al., 2011). As perspectives on teacher attention vary, so too do their exact definitions. Attending to student learning is often taken to encompass at least processes of perception and interpretation of information on student learning (e.g. M. Sherin et al., 2011a; Hammer et al., 2012). But, teachers' decision making processes for follow-up actions, for example, can also be found to get included (e.g. Jacobs et al., 2011). The importance of teachers gaining insight in student learning in the course of instruction is, however, emphasised by all.

In recent decades, interest in science teachers' attention to student learning as an important facet of teacher expertise has increased. Rosemary Russ (2018) describes how this development is motivated by constructivist learning theories and empirical findings highlighting the importance of instruction eliciting students' existing understanding. Making this observable and interpretable, means that instruction can be shaped in such a way that it allows students to develop their science ideas and reasoning using existing resources as a valuable foundation (Russ, 2018; Hammer et al., 2012). In a comparable fashion, researchers advocate attention to aspects of learning such as students' research practices (Hammer et al., 2012), and design practices (Watkins et al., 2021) to be able to respond to and support student learning during instruction. Attention to student learning has furthermore grabbed the interest of educational researchers and teacher educators because zooming in on attention allows for acknowledging the dynamic and situational use of teachers' cognitions and beliefs (Chan et al., 2020; Watkins et al., 2021). Rather than focussing on what teachers know, work into teacher attention pursues understanding of teachers' sensemaking of particular classroom events involving particular students. Attention has even been described as 'the missing link' between teachers' classroom practice on the one hand, and teachers' cognitions, beliefs and motivation on the other (Todorova et al., 2017, p. 276; building on Blömeke et al., 2015).

1.3 The complexity of design-based science and chemistry education

Despite attention's growing significance in research and teacher education, we know little about secondary school science teachers' attention in design contexts. Researchers working in elementary design settings have noted, however, that attending to student learning may be particularly important, yet complex in design-based classrooms (Watkins et al., 2018). Design-based approaches to learning typically engage groups of students in tackling multifaced, open-ended challenges, which can lead to a particularly wide variety of student ideas for teachers to make sense of (Watkins et al., 2018). The reform-based character of design-based science education further contributes to the complexity of attending to student learning in these contexts. Design has only relatively recently been introduced in secondary school science curricula (e.g. CvTE, 2014; NRC, 2012), and active engagement in design is not as common in science classrooms as scientific inquiry, for example (e.g. National Institute for Curriculum Development [SLO], 2018; Boesdorfer & Staude, 2016). Moreover, science teachers' conceptions about design and design-based teaching and learning can be rather naïve (e.g. Boesdorfer & Staude, 2016; Kolodner et al., 2003). Teachers' cognitions and practical experiences are, however, important resources in supporting their attention to student learning (e.g. Falk, 2012; Meschede et al., 2017; Santagata & Yeh, 2016). Science teachers may thus need assistance in learning to attend to student learning in the novel setting of design-based science education.

Design-based chemistry education may even pose additional challenges for teachers. Chemistry is one of the science subjects not often featured in design-based education research or in design-based lesson materials. Design-based learning is particularly often addressed in physics contexts (incl. Dare et al., 2014; Kolodner et al., 2003; Mehalik et al., 2008; Van Breukelen et al., 2015). But, while design in chemistry has overlap with technology and engineering design (Sevian & Talanquer, 2014), design practices and challenges also vary per discipline. Taking existing principles for design-based teaching and learning into chemistry classrooms may generate problems as well as missed opportunities. For instance, the typically recommended design activity of 'building' a prototype (e.g. CvTE, 2014; Kolodner et al., 2003), does not appear to cover common chemistry contexts like designing useful materials, efficient processes or novel synthetic pathways (Talanquer, 2013). And, design practices and pedagogical strategies like iteration and testing tangible prototypes (Puntambekar & Kolodner, 2005) may be more difficult to incorporate within the constraints of chemistry classrooms. Compare, for instance, a physics setting such as designing a mechanically-powered miniature car (Kolodner et al., 2003), with a chemistry setting like the design of gluten-free bread (Meijer, 2011). In the first case, students can quickly adapt or substitute an element of a prototype and conduct a new test (e.g. add tape to wheels to reduce friction; Kolodner et al., 2003). In the chemistry design situation, properties emerge from the interactions between myriads of particles at multiple scales, and students cannot just change their baking or baked bread (Meijer, 2011). Supporting design-based efforts in chemistry classrooms thus seems to call for chemistry-specific research.

1.4 Research aim, nature and context

To contribute to the field's budding understanding of teachers' attention to student learning in science education, and support efforts seeking to enhance teachers' expertise in design-based chemistry education, this research investigated *what* insight in student learning teachers can gain in the complexity of design-based chemistry education, and *how*. Because design-based education often has a range of goals, and can lead to a particular wide variety of student ideas to make sense of (Watkins et al., 2018), we were interested in examining attention to student learning in its multidimensionality. Multidimensionality refers to the various objects of interest that can grab a teacher's attention (Erickson, 2011). We also dived deeper into attention to students diverse chemical thinking in design contexts. Whereas chemistry is traditionally, and regularly still, taught as a collection of rather isolated facts, design offers a meaningful way for developing chemical thinking through active engagement in chemistry-authentic practice (Sevian & Talanquer, 2014; Bulte et al., 2005). Regarding how teachers can gain insight in student learning, we focussed on the use of sources of information on student learning. Design contexts offer access to a particular unique set of potential information which chemistry teachers may not typically use, such as students' design drawings and prototypes. These sources could, however, be revealing of students' thinking (English et al., 2017; Roth, 1994). We furthermore sought to develop new methods to facilitate the elicitation and characterisation of attention to student learning, which is notoriously difficult to capture because of its tacit and situated nature (e.g. Thomas, 2017).

We relied on qualitative research methods and extensive collaboration with a small group of chemistry teachers to meet our aim in this emerging area of research. This approach allowed in-depth examination of different matters of attention, and flexibility to pursue promising research directions. It also afforded recognition of attention as varying between teachers (e.g. Erickson, 2011), and tied to particular classroom situations and students (e.g. Van Es & M. Sherin, 2008). The collaborative and small-scale nature of the research furthermore provided access to chemistry teachers committed to design-based teaching and attending to student learning, in spite of its relative novelty. More specifically, we conducted our studies in the context of a Dutch professional learning community on design-based chemistry education. One of the main goals of this community was learning about formative assessment of student learning in design settings. Formative assessment centres on attention to student learning (Coffey et al., 2011), and has become a prominent notion in the Dutch educational landscape. Collaborating with teachers furthermore meant that we could 'consult their wisdom' (Kolodner et al., 2003, p. 543) to develop much-needed lesson materials for design-based chemistry education. Not only are well-founded lesson materials for design-based chemistry education in the Netherlands rather scarce, taking specific care to create opportunities for students to share their learning with teachers made the materials suitable research instruments to observe teachers' attention to student learning. Close interactions with the community's chemistry teachers additionally enabled the selection of particularly rich cases in order to meet our research aim.

1.5 Research outline

To meet this thesis's research aim, we conducted four in-depth studies involving different matters of teacher attention. Each of these studies is described shortly below, and presented in full in the subsequent chapters.

An initial study into the community teachers' ideas about teaching and learning in design-based chemistry education is presented in *Chapter 2*. Teachers' pedagogical ideas can act as resources supporting a teacher's attention to student learning (e.g. Falk, 2012; Santagata & Yeh, 2016). They furthermore influence teachers' adoption and implementation of curricular reforms (Jones & Carter, 2007; Van Driel et al., 2001). Through eliciting and analysing the six teachers' ideas about learning goals, student learning, instructional strategies and assessment (e.g. Magnusson et al., 1999; Van Gelder et al., 1973), this study thus sought to answer the question: *What pedagogical ideas do chemistry teachers have about design-*

based chemistry education?

In *Chapter 3*, teacher attention itself is the focal object of study. In light of the range of opportunities for student learning in design contexts, this study did not zoom in on attention to students' disciplinary thinking and practices as is often done (e.g. Luna et al., 2018; Richards, 2013; Watkins et al., 2021). Rather, we sought to examine the multidimensionality (Erickson, 2011) of a teacher's attention to student learning during a design-based chemistry project. To gain access to teacher attention, the study was embedded in a formative assessment environment, and made first-time use of a 'midstream modulation' approach to reflection conversations (Fisher, 2007; Fisher et al., 2006). This second study addressed the research question: *What aspects of student learning form the focus of a teacher's attention in a design-based chemistry context, and how does this attention change over the course of a design project and reflection conversations?*

Whereas these first two studies consider the range of aspects of student learning that may grab a chemistry teacher's attention in a design setting, the second set of studies dives specifically into attention to students' chemical thinking. *Chapter 4* concerns a study where we draw on the construct of teacher noticing (M. Sherin et al., 2011a) to examine teachers' in-the-moment attention to students' chemical thinking during design planning and drawing activities. In conversations between teachers and students surrounding students' design plans and drawings, students' thinking about science concepts may become observable (e.g. Roth, 1994; Guzey & Aranda, 2017; English et al., 2017). Using the chemical thinking framework (Sevian & Talanquer, 2014), this study examined the scope and evidence use of two teachers' noticing during such conversations in chemistry classrooms. This study was guided by the question: *What chemical thinking do chemistry teachers notice in conversations with student teams during design planning and drawing, and what sources of evidence do they use?*

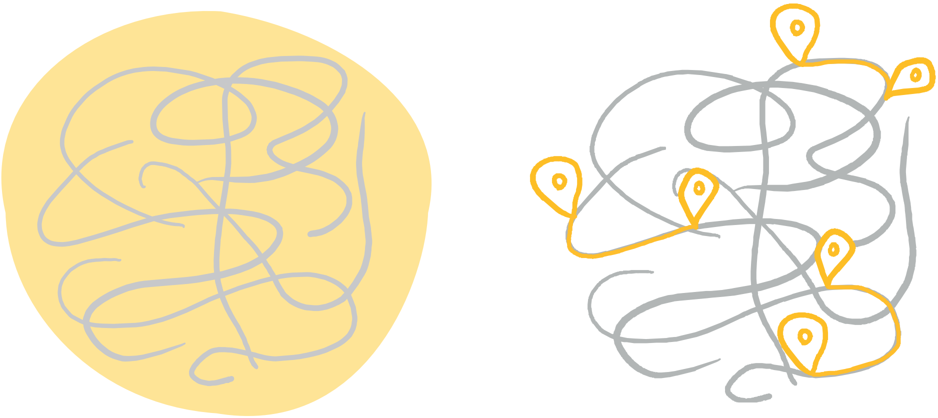
Chapter 5 presents the final empirical study of this thesis, involving a detailed investigation into how design-authentic sources of information can provide insight in students' chemical thinking in design contexts. As also highlighted by others (e.g. Wendell et al., 2019), researchers' in-depth analyses of evidence of learning can yield suggestions for productive ways in which teachers may attend to student learning. Design-authentic sources of information, such as annotated design drawings, might allow evaluation of students' conceptual sophistication within a design context. Building on work into students' (implicit) use of cognitive resources (incl. D. E. Brown & Hammer, 2008; Sevian & Talanquer, 2014), this study addressed the question: *How can design-authentic sources of information provide insight in students' use of conceptual understanding in chemistry in a design context?*

The final chapter of this thesis looks across these studies to conclude what studying matters of attention has revealed about what insight in student learning teachers can gain in the complexity of design-based chemistry education, and how. This last chapter also provides a general discussion of the results, addresses limitations and directions for future research, and highlights practical implications of the research.

Visual overview

Figure 1.1 provides a visual overview of the empirical chapters of this thesis. This representation seeks to highlight that the four empirical studies in this thesis look at different matters of attention to student learning in the complexity of design-based chemistry education.

The meandering lines in each quadrant of Figure 1.1 represent various aspects of student learning in design-based chemistry contexts (e.g. students' design practices, students' chemical thinking). The yellow underlayer in the top left quadrant (Chapter 2) represents a teacher's pedagogical ideas about teaching and learning in design-based chemistry education. The connected location icons in the top right corner (Chapter 3) represent a teacher's attention to an aspect of learning through time (note that the icons are positioned on different lines, so involving different aspects of learning). The black line in the two bottom quadrants represents students' chemical thinking in a design context. The focus icons signify a teacher's attention to students' chemical thinking (Chapter 4), and the magnifying-glass icons the attention of researchers (Chapter 5).



Chapter 2

Teachers' ideas about teaching and learning in design-based chemistry education

Chapter 3

Examining the multidimensionality and dynamicity of teacher attention in a design-based chemistry context

studies that involve…

multiple aspects of student learning

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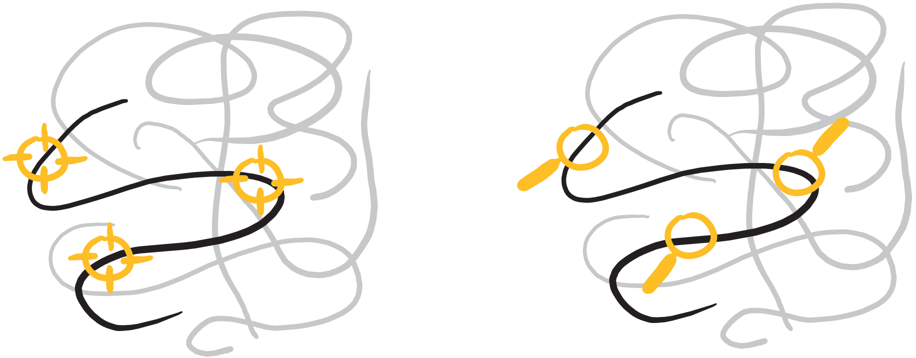
a specific aspect of student learning (namely chemical thinking)



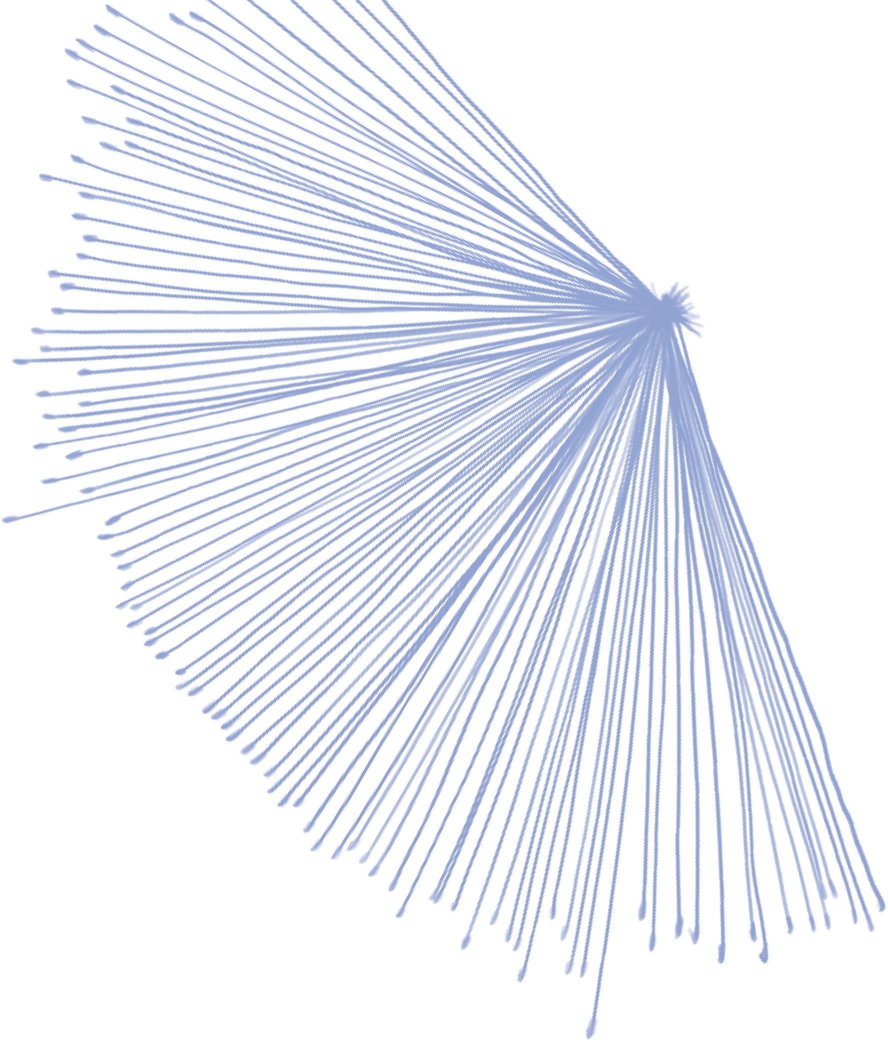
Chapter 4

Teachers' in-the-moment noticing of students' chemical thinking during design planning and drawing activities

Chapter 5

Characterising students' conceptual understanding using design-authentic sources of information

Figure 1.1. Visual overview of the empirical chapters of this thesis.



2 | Teachers' ideas about teaching and learning in design-based chemistry education

This text has previously appeared in modified form in:

Stammes, H., Henze, I., Barendsen, E., & de Vries, M. J. (2020). Bringing design practices to chemistry classrooms: Studying teachers' pedagogical ideas in the context of a professional learning community. *International Journal of Science Education, 42*(4), 526-546.

2.1 Introduction

Engaging secondary school science students in design practices is gaining importance around the world with recent reforms of science curricula (e.g. NGSS Lead States [NGSS], 2013; Board of Tests and Examinations [CvTE], 2014), and calls for integrated STEM education (e.g. Education Council, 2015; Fan & Yu, 2017). But, despite design being a central practice in the chemistry discipline, it has received little attention in chemistry education (Talanquer, 2013). Design does, however, offer a much-needed approach for meaningful chemistry education (Sevian & Talanquer, 2014; Van Aalsvoort, 2000). In traditional chemistry classrooms, chemistry is often taught as aggregations of isolated facts, and students can experience chemistry to lack relevance (Gilbert, 2006). Even in some context-based chemistry classrooms, teaching content can draw focus from actively engaging students in authentic chemistry ways of thinking and doing (Sevian & Talanquer, 2014). But, engaging students in chemistry talk and tasks helps them understand the meaning of what they are learning (Gilbert, 2006). And, engagement in and learning of both chemistry practices and content are important in preparing students for making chemistry-related decisions as scientifically literate citizens, and for potentially continuing a career in chemistry (Sevian & Talanquer, 2014). Situating learning chemistry in an authentic practice, like design, meaningfully connects chemistry content and practices around a shared practical purpose (Bulte et al., 2005). Researchers have found that design in chemistry education can, for example, promote students' understanding of fundamental ideas in chemistry (Apedoe et al., 2008; Meijer et al., 2009), and students' real-world problem-solving skills (Fortus et al., 2005).

Teachers, however, play an essential role in realising the potential of design-based teaching (Kolodner et al., 2003; Schnittka & Bell, 2011). But, although teachers' ideas about teaching and learning are known to influence the implementation of educational reforms (Jones & Carter, 2007; Van Driel et al., 2001), little is known about chemistry teachers' views on integrating design practices in their school subject. Many studies on design-based science teaching, and teachers in such settings, can be found to zoom in on design in physics contexts (e.g. Dare et al., 2014; Kolodner et al., 2003). Also, curricula (e.g. CvTE, 2014; NGSS, 2013) and research studies (e.g. Fortus et al., 2004; Guzey et al., 2016; Reynolds et al., 2009) offer design-based learning frameworks or examples of chemistry design contexts without discussing what implementing these means for chemistry teachers teaching chemistry. But, taking general teaching and learning principles for design in science education into chemistry classrooms might cause teaching and learning problems and missed opportunities. For example, though design in chemistry has overlap with technology and engineering design (Sevian & Talanquer, 2014), design processes vary per discipline (Berland et al., 2014). And, using design activities and terms like 'constructing artefacts' (Fortus et al., 2005), 'building', and 'products' (CvTE, 2014) may increase coherence across science subjects in school, but might not match well with common chemistry design contexts like ‘synthesis’ (Bensaude-Vincent, 2009), and developing efficient ‘processes’ (Talanquer, 2013). Additionally, engaging chemistry students in a typical chemistry design setting like making new substances or materials may be challenging for teachers. When students design gluten-free bread (Meijer et al., 2009), for example, students cannot quickly change and retest their design. Design iterations are, however, important as they stimulate students to continuously refine their design, conceptual understanding and practices (Puntambekar & Kolodner, 2005). These examples suggest that chemistry teachers might have or need specific ideas about teaching and learning for bringing design into their school subject.

In this study, we will explore chemistry teachers’ ideas about design in chemistry education. Our research focusses on teachers’ pedagogical ideas, that is, what design in chemistry education means to them regarding learning goals, student learning, instructional strategies and assessment. Design processes in chemistry have been described as being relevant in different chemistry contexts, such as involving synthesis, analysis and transformation (Sevian & Talanquer, 2014), and chemistry products and processes (e.g. Favre et al., 2008). Because chemistry teachers may similarly associate design in chemistry education with a variety of chemistry design contexts, we will look at design in chemistry from this broad perspective when exploring teachers’ pedagogical ideas.

Our study’s participants are Dutch chemistry teachers who, like teachers in several other countries, are encouraged to bring design to their classrooms because of a recent curriculum reform (CvTE, 2014). We study these teachers’ pedagogical ideas in the context of a professional learning community on design in chemistry education, which we expected would help elicit teachers’ (partly tacit) ideas. As actively engaging students in design does not seem to be a typical teaching approach for chemistry teachers (Boesdorfer & Staude, 2016), a better understanding of teachers’ views could support a change to integrate design practices in chemistry education (Talanquer, 2013). Insight in teachers’ ideas can inform future research efforts, and the development of lesson materials, teaching strategies and professional development programmes (Levitt, 2001; Van Driel et al., 2001).

2.2 Theoretical background

While research practices have held a particular prominent place in chemistry education and research, design practices have received much less attention (Talanquer, 2013). Regarding teachers’ ideas in this context, an American survey study, conducted before adoption of the Next Generation Science Standards (2013), did find that chemistry teachers can have naïve conceptions about engineering design (Boesdorfer & Staude, 2016). Also, teachers are often described to have difficulties in connecting science and design to stimulate student learning (e.g. Crismond & Adams, 2012; Guzey et al., 2017). Reviewing examples in literature and curricula on design in chemistry and science education does reveal multiple possibilities for promoting learning chemistry through design, which we could also come across in our exploration of chemistry teachers' pedagogical ideas.

2.2.1 Stimulating learning of chemistry content and practices through design

Design can be implemented as a vehicle for students to develop chemistry content knowledge (Fortus et al., 2004). Students construct new knowledge in the context of a design problem (Fortus et al., 2005), and need this knowledge to successfully complete the challenge (Kolodner et al., 2003). When students experience a need-to-know during their design process they are introduced to new concepts, for example, through reading information, watching videos, doing computer simulations, teacher-led demonstrations, asking experts, explicit teaching or conducting experiments (Fortus et al., 2004; Puntambekar & Kolodner, 2005; Van Breukelen et al., 2015). Fortus et al. (2004) found that students can develop understanding of electrochemistry by being embedded in the context of designing environmentally-friendly batteries. Designing a heating or cooling system relying on chemical energy can help students gain knowledge of atomic interactions, reactions and energy (Apedoe et al., 2008). Although Apedoe and her colleagues, like others (Kirschner et al., 2006), were concerned that concepts might not be learned as well or as quickly through design, their study's teachers reported they could cover other content more quickly because of students' improved understanding of fundamental ideas in chemistry.

Another option is viewing design primarily as a context for students to apply chemistry content knowledge. The Dutch curriculum, for example, requires students to learn to 'use relevant concepts' during a design process (CvTE, 2014). Applying concepts when solving a design problem means students can test and deepen their understanding (Berland et al., 2014; National Research Council [NRC], 2012). This view can take the form of teaching concepts first, and having students complete a design challenge afterwards (as in Schnittka & Bell, 2011).

Improving students' reasoning in chemistry is also a possible goal of design in chemistry education. Designing gluten-free bread, for example, was a practice used to develop students' reasoning regarding structure-property relationships (Meijer et al., 2009). Reasoning in design contexts also pops up in science curricula. The NGSS, for example, mention 'engaging in argument from evidence' to 'identify the best solution to a design problem' (NGSS, 2013). Reasoning can also help students learn from design experiences, and transfer their learning to other settings (Kolodner et al., 2003). To encourage students to reason when designing, and to use conceptual understanding in their reasoning, students can be asked to explain design ideas to peers, discuss test outcomes, or justify design decisions (Apedoe et al., 2008; Kolodner et al., 2003; Silk et al., 2009). Research on teaching and learning to reason in chemistry through design is still scarce though, as are studies into applying and developing chemistry content knowledge through design.

Design in chemistry education is also seen to take shape as 'designing investigations' (e.g. Girault & d'Ham, 2014). By designing or optimising experimental procedures, students can learn to solve a scientific problem, such as determining the concentration of dye in grenadine (Girault & d'Ham, 2014). Students can also be asked to design an investigation in the context of a design project. Doing research helps students build knowledge of materials and key design variables so they can make informed design decisions (Crismond & Adams, 2012). Performing research activities in a design context can also stimulate students' learning of scientific practices and new science concepts (Kolodner et al., 2003). Especially before design was emphasised in curricula as a relevant practice in itself, design-based science efforts aimed to improve students' scientific practices and knowledge (e.g. Puntambekar & Kolodner, 2005; Silk et al., 2009). As Fortus et al. (2004): 'Our goal in these [design] units is not to instruct the students about design; we want to engage them in design in order to learn science' (p. 1085).

Currently, the importance of students developing design practices such as 'defining problems' and 'designing solutions' (NGSS, 2013) have been gaining attention in science education. A few specific contexts for engaging chemistry students in design (thinking) can also be found in such science curricula. In the NGSS a chemistry-specific design example reads: 'design, build and refine a device that works within given constraints to convert one form of energy into another form of energy' (NGSS, 2013). And, Dutch chemistry students are expected to learn to use their understanding of green chemistry to explain designs of industrial processes (CvTE, 2014). However, unlike for design in higher chemistry education (e.g. Favre et al., 2008; Fung & Ng, 2018), what learning or teaching 'to design in chemistry' could mean at the secondary school level is not well described.

In addition to the above mentioned views, design practices in chemistry education may also be found in the form of 'designing models' (e.g. Chang et al., 2010; Justi & Gilbert, 2002), and as an instructional approach to teach analysis, synthesis and transformation practices (Sevian & Talanquer, 2014). Although we do not aim to present an exhaustive overview, these examples indicate that there are multiple (often interrelated) options for stimulating student learning of chemistry content and practices through design. Each focus calls for specific ideas regarding learning goals, student learning, instructional strategies and assessment. Where the examples above primarily express the views of curriculum developers and researchers, this study explores what chemistry teachers think of design in chemistry education.

2.2.2 Teacher pedagogical ideas

Teachers' ideas about teaching and learning significantly influence their implementation of innovative teaching approaches, and science education reforms (e.g. Jones & Carter, 2007; Roehrig & Kruse, 2005; Van Driel et al., 2001). Although the relation between teacher cognitions and behaviour is complex (Jones & Carter, 2007), teachers' ideas have been found to influence their teaching of design-based science education. Researchers noticed, for example, that teachers are often unfamiliar with the importance of instructional strategies like iteration, reflection and discussion to stimulate students' learning of science through design, and instead choose to spend too much time on construction activities (Kolodner et al., 2003). And, science teachers developing their own design projects tend to overlook activities encouraging students to communicate design and science ideas, because such activities are thought of as requiring too much class time (Guzey et al., 2016). Teachers can be stimulated to use such critical teaching strategies by developing instructional frameworks that make connections between science and design explicit for students as well as teachers (Kolodner et al., 2003). Gaining insight in chemistry teachers' ideas about teaching and learning in the context of design in chemistry education could support developing such frameworks for chemistry education. A better understanding of chemistry teachers' pedagogical ideas, and potential differences between teachers' ideas, could also form a starting point for the design of professional development programmes (Van Driel et al., 2001) helping chemistry teachers to bring design practices to their classrooms.

Studying teachers' ideas about teaching and learning, however, can be challenging. Teachers' cognitions are often tacit in nature, and difficult to elicit (Verloop et al., 2001). Teachers can, for instance, lack the vocabulary to articulate their ideas, and an extended period of time may be required to capture ideas influencing teachers' practice (Loughran et al., 2004). To capture teachers' ideas, researchers can use more than one elicitation instrument. Examples of such instruments are: semi-structured interviews (e.g. Henze et al., 2008), stimulated-recall interviews (e.g. Nilsson, 2008), teacher group discussions (e.g. Loughran et al., 2004) and teacher lesson forms (e.g. Henze & Barendsen, 2019). Teachers can also be stimulated to articulate their pedagogical ideas by basing formulations of questions and prompts on well-known pedagogical elements. Four pedagogical elements often used are: learning goals, student learning, instructional strategies and assessment. These interconnected elements also form the foundation of instructional frameworks (e.g. Dochy et al., 1996; Van Gelder et al., 1973), (chemistry) teacher education programmes (e.g. Aydin-Günbatar & Demirdöğen, 2017; Henze & Barendsen, 2019) and teacher cognition models (e.g. Magnusson et al., 1999). In other studies into teachers' ideas in design-education contexts, using these four pedagogical elements indeed provided insight in teachers' pedagogical ideas (Rahimi et al., 2016; Vossen et al., 2019).

Throughout this study, we use the term 'ideas' because, especially in our reform-based context, we expect to elicit a mix of teacher knowledge, beliefs, conceptions and intuitions (Verloop et al., 2001). We expect this study's Dutch teachers to have formed some ideas about design in chemistry education, as they have been teaching a new curriculum emphasising design for three years. However, teachers might not yet have developed a more expert type of pedagogical knowledge and beliefs.

2.2.3 Context of the study: a Dutch professional learning community

The new Dutch science curriculum, introduced in 2013, required all science teachers to address nine so-called ‘technical design skills’ (incl. ‘analysing and describing a technical design problem’; ‘drawing up a list of requirements’; ‘making a well-argued design proposal’; ‘presenting a design process and designed product’; CvTE, 2014). Dutch science students should learn to implement these skills in science contexts while using (science) concepts, and valid arguments. The chemistry-specific part of the Dutch curriculum (grades 9–11 or 12) additionally relates design to contexts like sustainability, industrial processes, materials and health (CvTE, 2014). To help chemistry teachers meet their expressed need for design-based lesson materials for chemistry education, we initiated a two-year-long professional learning community (PLC) for Dutch chemistry teachers (Voogt et al., 2015). The PLC activities would be centred around jointly developing, testing and evaluating design projects and teaching strategies for design in chemistry contexts. This PLC set-up also allowed us to research teaching and learning regarding design in chemistry education. The study reported here takes place in the beginning of this PLC as we are interested in exploring what design in chemistry education means to chemistry teachers (without an intensive professional development programme on the topic having influenced their ideas yet).

In the beginning of the PLC, the PLC’s chemistry teachers all implemented a 9th grade design project (‘Expedition Toothpaste’) in one of their own chemistry classes. In the first PLC meeting, shortly before the teachers implemented this project, the teachers and researchers discussed the design project. Teachers were interested in trying out this design project, and improve it later as a PLC. In the project, chemistry students design a toothpaste which survivalists stuck at a deserted island can make (this setting resembles that of popular Dutch television shows). The design project was meant as an introduction for students (and teachers) to design (teaching) practices, and the toothpaste context did not necessarily require addressing chemistry concepts (based on the notion of ‘launcher units’; Holbrook et al., 2001). Teachers could choose to make connections to curricular chemistry topics, such as structure-property relationships, and acids and bases. The projects’ activities were based on the design requirements of the Dutch curriculum, and included Leaning-By-Design elements (incl. moving between design and research, and sharing and discussing ideas and outcomes throughout the project; Kolodner et al., 2003). To improve the toothpaste project in the PLC, teachers kept a record of their teaching and students’ learning during project implementation.

2.3 Research design

We explored chemistry teachers’ pedagogical ideas qualitatively in the context of the PLC. This qualitative design allowed us to investigate chemistry teachers’ ideas in depth, and explore what teaching and learning in the context of design in chemistry education means to teachers (Babbie, 2016; Cohen et al., 2018). The research question guiding our study was:

What pedagogical ideas do the Dutch PLC's chemistry teachers have about design in chemistry education?

2.3.1 Participants

All of the six chemistry teachers of the PLC participated in this study. The teachers had responded to an open invitation (Cohen et al., 2018) for secondary school chemistry teachers to join the PLC. Invitations had been distributed through the regional teacher professionalisation centre, and researchers' personal networks. Teachers were informed about the research aims, and gave their consent. The teachers had varying chemistry and design teaching experiences (see Table 2.1; teacher names are pseudonyms). All teachers had a master's degree in (bio) chemistry, and were qualified for teaching upper secondary school chemistry education. Joanne also had a PhD in chemistry, and Ruben and Vera had professional design experience (see Table 2.1). Ruben and Vera were colleagues at the same school.

2.3.2 Data collection

We collected data on teachers' pedagogical ideas about design in chemistry education using two instruments: semi-structured interviews (Brinkmann & Kvale, 2015) and lesson forms accompanying teachers' implementation of the toothpaste design project (similar to Henze & Barendsen, 2019). To elicit what design in chemistry education means to the teachers, we based questions in the interview and forms on the four, general pedagogical elements of goals and objectives, student learning, instructional strategies and assessment. Both data collection methods were employed at the start of the two-year-long PLC (within the first few months, depending on when a teacher timed implementation of the design project), and interviews took place before teachers implemented the project. As researchers have observed that science teachers in a professionalisation setting tend to implement a design-based project in their own way first, after which they can – with help – learn about important components of such projects (Kolodner et al., 2003), we expected that the lesson forms as well as the interview data would give us insight in the pedagogical ideas of this group of teachers beginning to learn about design in chemistry education. We also expected that being an active member of a PLC about design in chemistry education would help bring teachers' (tacit) pedagogical ideas to the surface.

Semi-structured interview

In the interview, conducted first, we asked teachers to talk about their teaching experiences regarding design in chemistry education, and design in other school subjects. Subsequent questions were based on the four pedagogical elements of goals and objectives, student learning, instructional strategies and assessment (as in Loughran et al., 2004 and Henze et al., 2008) tailored for our study's context. Interview questions included: According to you,

Table 2.1. Participants' reported teaching and professional design experiences.

	Teaching experience secondary school	Design teaching experience		Professional design experience
		in general STEM course	in chemistry course	
Joanne	Over 20 years	Includes implementing project on biomedical design (10th grade)	Includes developing and implementing project on chemical Rube Goldberg machines (9th grade), and implementing upper secondary school project on drugs	(None)
Ruben	About 5 years	(None)	Includes developing and implementing project on fireworks (10th grade), and project on soaps and fragrances (11th grade)	Chemical process engineering
Vera	First year of teaching	(None)	Includes developing and implementing project on rocket fuels (10th grade), and implementing project on soaps and fragrances (11th grade)	Biotechnological engineering
Peter	About 8 years	(None)	(None)	(None)
Lucy	About 2 years	(None)	(None)	(None)
Marcel	About 8 years	Includes implementing project on 'dropping an egg' (8th grade), and upper secondary school project on water purification systems	(None)	(None)

what are important learning goals of design in chemistry education, and why? Do you think it is important that students design in chemistry, and why (not)? What difficulties for students do you expect? How would you address these difficulties? What other factors influence your teaching regarding design in chemistry? How would you wrap up a design project? How would you assess whether students meet your learning goals? How would you summatively assess student learning? Finally, we asked teachers what topics or settings they thought suitable for designing in chemistry education, as we would be developing chemistry design projects in the PLC (some of which involving teaching chemistry content through design).

The semi-structured interview took place at teachers' schools, or their home (for Lucy). Interviews took 60–75 minutes, and were audiotaped and transcribed.

Lesson forms

Secondly, we collected data through the forms teachers filled out when implementing the toothpaste design project in one of their chemistry classes. Although the teachers implemented the same project, they could formulate their own learning goals throughout the project, and add, remove or adapt activities as they saw fit. In the forms, teachers recorded their ideas about their teaching, their students, and ideas for improving the project. Similar as Henze and Barendsen (2019), we gave them three forms: one for whole-project planning, one for whole-project evaluation, and one for evaluating a single lesson and looking forward to the next. In this study, however, we simplified these forms using the same type of questions in each form. Questions of the interview were adapted for the context of the toothpaste project, for instance: What are your learning goals for this project? (project planning form); Have your students achieved the learning goals, and how do you know that? (lesson evaluation form; project evaluation form). And, questions regarding adapting and improving the project were added: Will/did you adapt elements of the project, why and how? (all forms); How should the project, or the project's teaching materials be adapted, and why? (lesson evaluation form; project evaluation form). Teachers implemented the project in five to six lessons. They were encouraged to fill out the digital forms regularly, and were sent a reminder if necessary.

2.3.3 Data analysis

In analysing chemistry teachers' ideas about design in chemistry education, we stayed close to the teachers' views (Saldaña, 2016). And, to further our theoretical understanding, we looked for patterns in the pedagogical ideas across the six teachers (as suggested by Van Driel et al., 2001). We analysed the data in three cycles. Each cycle had an iterative character, and involved constant comparison, memo writing, and rereading codes, transcripts and lesson forms (Saldaña, 2016). Throughout data analysis, we promoted consensus and consistency by discussing codes, categories and patterns (initially formulated by the first author) intensively between the first and second author, and regularly with all authors. In this description of the data analysis, we use analysis examples of Ruben's data (a teacher with many pedagogical ideas).

In the first cycle, we coded teachers' pedagogical ideas in the interview transcripts and lesson forms using Atlas.ti. To identify pedagogical ideas in the data, we used the four pedagogical elements (goals and objectives, student learning, instructional strategies and assessment) as a lens. This deductive aspect helped us select ideas relevant to our research focus, as teachers had also shared ideas about, for example, school context and self efficacy. First cycle codes expressed teachers' ideas in their own words (Saldaña, 2016), and contained a reference to a specific pedagogical element. Examples of first cycle codes are: ‘formulating a clear design goal’ (goals and objectives), ‘some students can immediately [formulate a] good [design problem], others find it very difficult’ (student learning), and ‘practice formulating design problems using cases’ (instructional strategy).

In the second cycle, we condensed the data further, and worked towards finding patterns (Saldaña, 2016). By grouping and regrouping a teacher’s first cycle codes, we formulated second cycle codes describing teacher ideas within and across pedagogical elements. For example, the first cycle codes examples mentioned above together describe Ruben’s idea that design in chemistry education means ‘teaching students to formulate a design problem’. Through this process, five categories emerged into which ideas of all the six teachers could be classified. The teachers related design in chemistry to: teaching design (category 1), teaching chemistry content (category 2), teaching research (category 3), and teaching soft skills (category 4). ‘Soft skills’ were skills teachers viewed as transferable to many other settings (like ‘making mistakes’ and ‘working together’). Using terminology from the research field of pedagogical content knowledge, these four categories emerged based on types of large grain size ‘content’ teachers referred to (Carlson & Daehler, 2019). The fifth category of pedagogical ideas emerged as some of teachers’ pedagogical ideas were not related to ‘content’, but to teachers seeing design in chemistry as a project-based, hands-on and learner-centred way of teaching (category 5). This second analysis cycle led to tables of categorised pedagogical ideas per teacher (see Table 2.2 for an example).

In the last cycle, to deepen our understanding, we looked for additional patterns (similarities, differences, frequencies, incoherencies, etc.; Saldaña, 2016) in the ideas across the six teachers. We looked for patterns within each category of ideas, and across the categories. Regarding pedagogical ideas in category 1, for example, three patterns emerged: teachers said to teach design as a general process or problem solving approach, teachers were simplifying the curricular design requirements, and teachers preferred to engage students in designing ‘something concrete’. In the findings section, we present descriptions of the patterns thus found.

Table 2.2. Ruben's pedagogical ideas per category (result of the second analysis cycle).

	Design in chemistry education means (to Ruben)
Category 1 Relating design in chemistry education to teaching design	Teaching design as a stepwise process
	Teaching the logic of a simplified form of the design cycle
	Teaching most important design skills of the curriculum
	Teaching students to formulate a design problem
	Teaching students to generate partial solutions
	Teaching design throughout secondary school
	Engaging students by making a concrete product
	Using the design cycle as theoretical background
	Using examples and students' practical design experiences
	Having students share final designs
	Having students reflect on the design process
	Assessing intermediate and final design products using criteria
	Not knowing (how to assess) what students learn regarding design
Category 2 Relating design in chemistry education to teaching chemistry content	Teaching to look up chemistry theory to answer a design-related question
	Stimulating students to practice micro-macro thinking when designing
	Possible teaching approach for most chemistry concepts, but time consuming
	Possible teaching approach for all students, but makes senior students nervous
	Difficult to learn chemistry concepts well through design
	Stimulating concept learning early in design project
	Alternating concept- and design-focused lessons and projects
	Choosing design setting related to multiple chemistry topics
	Using a design-based approach from first year chemistry education onwards
	Practicing concept-based final assessment during design project Setting content-based criteria for design-based final assessment
Category 3 Relating design in chemistry education to teaching research	Teaching why research is needed when designing
	Using design as a practical approach to teach research
	Teaching most important research skills
	Teaching research throughout secondary school
	Teaching the logic of a simplified form of the research cycle
	Teaching students to design a simple experiment
	Teaching students to formulate a research question
	Stimulating students to control variables
	Teaching students to take lab notes
	Teaching students to analyse data and formulate quantitative and qualitative results and conclusions
	Teaching students to summarise and share research outcomes

Table 2.2 continued

Category 4 Relating design in chemistry education to teaching soft skills	Stimulating students' collaborative skills Stimulating students' organising skills Students need to get used to things going wrong
Category 5 Design in chemistry education as project-based, hands-on learner-centred teaching	Motivating students through hands-on activities Stimulating students' feeling of involvement and responsibility Basing activities and student workbooks on students' intuitive approach Making different agreements on using lab materials Giving students extra time to do hands-on activities Nudging students when they are stuck by asking questions Sharing and clarifying expectations and assessment criteria more regularly Using student workbooks, asking questions, observing and having students talk as assessments Experiencing difficulties in fairly and summatively assessing group projects Assessing students' personal development to understand their learning

2.4 Findings

Through analysing the collected data, we found that teachers' pedagogical ideas could be divided into five categories. Teachers related design in chemistry education to: teaching design (category 1), teaching chemistry content (category 2), teaching research (category 3), and teaching soft skills (category 4). Teachers also had pedagogical ideas about design in chemistry education as a project-based, hands-on and learner-centred way of teaching (category 5). Both within and across these five categories, we found patterns in teachers' pedagogical ideas about design in chemistry education. We give thick description of these patterns in this findings section.

2.4.1 Category 1 – Relating design in chemistry education to teaching design

To the teachers, teaching students to design meant teaching design as a more general process or problem-solving approach, and simplifying the curriculum standards regarding design. A third pattern emerged as teachers preferred to engage chemistry students in designing 'something concrete', which did pose challenges.

Teachers took a more general perspective on teaching design by teaching the practice as a universally-applicable, step-wise process or problem-solving approach. Peter, for instance, taught students to design by teaching them to: 'work stepwise to solve a problem'. Joanne said to teach students to 'go through a certain process', and that this process was 'much more important to assess' than the quality of students' final design. Teachers were also simplifying the Dutch curriculum standards which prescribed nine technical design skills (based on the steps of a design cycle) for science students to learn in secondary school. Teachers reduced the variety of design skills to be learned. For example, Ruben: 'Students need to […] be able to implement the most important design steps'. Ruben focussed especially on teaching students to formulate a design problem, and to generate 'partial solutions' (thinking of several design ideas per function of a design). Simplifying the curricular design standards would help students learn to design, and motivate students. In teaching design, teachers preferred to engage students in designing something concrete (as opposed to, for instance, drawing a process design). This would motivate students more, and allow them to judge the quality of their design more easily. However, a preference for concrete products did pose challenges. Peter:

> You'd like to give students the freedom to build something, which I think is very difficult in chemistry. In physics you can say 'Here's some wood and a fretsaw, go build a car' […]. But in chemistry I can't picture that, because there's not that much space for experimenting, as you need to be careful.

2.4.2 Category 2 – Relating design in chemistry education to teaching chemistry content

In the second category of pedagogical ideas, relating design in chemistry education to teaching chemistry content, teachers viewed design as a way for students to apply 'existing' chemistry content knowledge, and were apprehensive about teaching new chemistry concepts through design.

Joanne: 'Design is another way for students to apply their [chemistry] knowledge, […] another context you could say'. Such a context could have benefits for student learning. Lucy: 'Students will remember everything better […]. They will realise that topics from previous chapters can come back when designing'. Recalling experiences from a physics-design project, Marcel shared a strategy for helping students connect chemistry concepts to their design:

> For example, [by saying] 'You just tested [the design], you saw it didn't work, now think about how you can improve it; we just talked about forces, use that'. That was about physics, not chemistry, but you can involve concepts this way.

However, for some teachers, finding a suitable design context for this approach was challenging. Joanne: 'I think that's quite hard […], because I'm thinking of linking it to a concept … '. Teachers were apprehensive about students developing new content knowledge through design. Peter: 'The anxious part of such a fun teaching approach is, will addressing content go as quickly as through whole-classroom teaching?'. Ruben preferred to address most concepts at the start of a design project, as it was difficult to teach chemistry concepts well through design. A design-based teaching approach to teach new chemistry concepts (one of the PLC's topics) was deemed most suitable for students who already knew 'the basics' of chemistry, and were not in their final year of school in which passing the national exams was the primary focus. In their implementation of the toothpaste design project, teachers did not focus on making connections between design and chemistry content. Joanne, for example, wrote to have 'left acids and bases out of it, because of time and because groups didn't ask me about it'.

2.4.3 Category 3 – Relating design in chemistry education to teaching research

In the category of pedagogical ideas relating design in chemistry education to teaching research, we found two different perspectives. Teachers either considered students doing research in a design context mainly as a way for students to improve their research skills, or as a way for students to improve their design by applying research skills.

Ruben, Peter and Lucy held the first view. Ruben considered design 'a practical approach to help students develop research skills in chemistry', and addressed many different research skills when implementing the toothpaste project. Lucy wrote in the project preparation form to have only research-related learning goals for the toothpaste design project: wanting students to learn to 'conduct research themselves, and say whether something meets the design requirements' and 'conduct research in a group context'. This would help prepare students for doing their big, open-ended science study at the end of secondary school. Joanne, Vera and Marcel held the other perspective: seeing research activities primarily as a way for students to improve their designs. Joanne: 'Students learn that research is necessary to decide which solution is best for a certain design requirement' and 'that [research] can lead to conflicting results for the different design requirements, so you need to make decisions'. These teachers addressed research activities 'as part of the design process' during the toothpaste design project. Vera: 'Students learn to explain why designing a product also requires doing research'.

2.4.4 Category 4 – Relating design in chemistry education to teaching soft skills

In the fourth category of ideas, teachers saw design in chemistry education as a way to address important soft skills which they could not in 'normal' chemistry lessons. Teachers also realised engaging students in design meant teaching soft skills they did not personally see as being important in chemistry education, but which students needed when designing.

Teachers saw design in chemistry education as an opportunity for helping students apply or develop soft skills they deemed important, but could not easily address in typical chemistry lessons. Joanne: '[Design] gives students the opportunity to use their creativity. They can give it their own spin, more than when they are working on a theoretic topic and making exercises'. Vera valued design primarily as a way to teach students to think for themselves, and make their own decisions because chemistry students would often simply follow cookbook recipes when doing lab work. A design-based approach also meant to teachers addressing soft skills they did not necessarily value, but which students needed when designing (mostly involving collaboration, independent-working and planning skills). Ruben: 'Planning is also a skill you want them to learn, but I don't know if I would do that straight away'. However, during the toothpaste project, Ruben noticed that students 'had difficulties in organising their own work', and he decided to help them by teaching them how to make a 'good action plan'.

2.4.5 Category 5 – Design in chemistry education as project-based, hands-on and learner-centred teaching

To the teachers, design was a 'different' teaching approach for chemistry education which meant weighing off contrasting ideas regarding student learning, instructional strategies and assessment.

Designing's hands-on, learner-centred and project-based aspects made it a different way of teaching according to the teachers. Peter: 'I kind of see it as […] just something different'. This teaching approach provided teachers with interesting opportunities for teaching and learning. However, it also came with big challenges. For example, such a teaching approach was seen as both motivating students (especially the hands-on activities), and causing potential motivation problems. Joanne: 'students sometimes see such projects merely as a way to improve their grade average'. Also, on one hand, teachers felt this type of teaching meant not answering students' questions directly, letting students work in their own tempo, not giving grades, and allowing students to follow their own intuition. On the other hand, key activating and motivating strategies for most teachers were telling students what to do, and giving students a grade. Vera: 'I [end up] continuously telling them what needs to be done, because otherwise, generally, not much is happening'. As another example, whole-classroom discussions and presentations were valued as an opportunity for students to learn from each other, and for the teacher to gain insight in students' learning. Contrastingly, such activities were also seen as 'time eaters' and disrupters of students' team-work process. Teachers were all balancing such ideas, but seemed to make different decisions for their teaching.

2.4.6 Across the five categories

Looking at teachers' pedagogical ideas across the categories showed teachers valued design not as a goal, but as a teaching approach for chemistry education. Also, teachers had a personal focus in using design as a teaching approach.

Although teachers had pedagogical ideas about teaching design, they did not see design in chemistry education to be important in itself. For example, Lucy: ‘I don’t think design is particularly important in chemistry education. But, I think students develop so much skills through design which are useful for their future studies or jobs’. To Lucy, these more relevant skills were working independently, not being afraid of making mistakes, and doing research. Teachers had a personal focus in implementing design as a teaching approach. Joanne, for instance, saw design mostly as a context for applying chemistry concepts, and a way to motivate students for her lessons: ‘[…] I’ve noticed design can get students excited, especially those who are normally waiting till the lesson is over’. Marcel wanted students to develop skills like creativity and problem solving through design, and continued with: ‘So that’s not tied to chemistry, but well, if we’re designing in chemistry education, then let it be a chemistry design’. Some teachers did refer to ‘ties’ between chemistry and design. Ruben wrote to teach students design skills during the toothpaste project because of the curriculum, and because ‘design skills play a role in many chemistry jobs’. Vera addressed design skills because ‘students don’t realise that products they use daily didn’t just come into existence’. However, these teachers also valued design in chemistry education as a teaching approach, not as a goal.

2.5 Discussion of findings

Bringing design practices to secondary school chemistry classrooms could foster meaningful chemistry education. Although chemistry teachers are key in realising design’s potential for student learning, little is known about their views on this topic. To reduce this gap in literature, we explored what pedagogical ideas chemistry teachers have about design in chemistry education. We studied teachers’ ideas in depth in the context of a newly initiated Dutch professional learning community. As in other countries, a recent curriculum reform in the Netherlands was encouraging chemistry teachers to engage their students in design.

The categories and patterns found in teachers’ pedagogical ideas indicate that, even in a context where design is the central theme, chemistry teachers can adhere to somewhat traditional views on chemistry education by valuing design as a way to address chemistry content knowledge and research practices. Teaching of chemistry content and ‘scientific’ practices are long-established emphases in chemistry curricula and classrooms (Gilbert, 2006), which may cause teachers to believe these are more important than teaching design. Teachers’ ideas may also have been influenced by their familiarity with teaching research and chemistry content as opposed to teaching design. A focus on science content and practices was found as well in our review of literature on design-based chemistry and science education. Fortus and colleagues (2005) explain their choice of teaching science over teaching design by stating that teaching and learning design is a ‘very useful activity’ but that design was not included in the science standards. In the context of this study, design practices were part of the curriculum, but, as with many curriculum reforms (e.g.

Jones & Carter, 2007), this did not lead the chemistry teachers to believe teaching design to be a relevant goal of chemistry education. Indeed, design is sometimes described as a possible pedagogy for chemistry education, rather than as a practice to learn in itself (Sevian & Talanquer, 2014). And, although researchers may suggest using design to help students develop understanding of new chemistry concepts (e.g. Fortus et al., 2004; Meijer et al., 2009), which has led to efforts in the Netherlands aiming to stimulate context-based science education, the teachers preferred teaching chemistry content before engaging students in design activities (which is more common among science teachers; Guzey et al., 2016). The research activities embedded in the toothpaste design project could have also contributed to teachers relating design to teaching research. Still, this category of pedagogical ideas (like the other categories) appeared in both the interview and lesson form data. Perhaps teachers recognised that boundaries which are often perceived to exist in science education between design and research are especially fuzzy in the context of chemistry (Talanquer, 2013).

Although the teachers remained close to more traditional views of chemistry education concerning students' chemistry content knowledge and research practices, they were taking a more contemporary perspective by valuing design as an approach to address soft skills (like creativity and meta-cognition). Teachers felt teaching approaches they commonly used in chemistry education did not allow them to stimulate students' use and development of these important skills. Teachers' notion of design being a project-based, hands-on and learner-centred teaching approach seems to have promoted this association. Increasing attention in Dutch schools on teaching 'twenty-first century skills' may have also influenced this idea. Indeed, design-based science education has been described as lending itself to help develop students' complex cognitive and social skills (Kolodner et al., 2003). We saw the teachers felt very strongly about the importance of certain soft skills (skills which varied per teacher). To them, design seemed to mean having a rare opportunity to address such skills in chemistry education which highly motivated them to include design practices in their teaching.

Teachers' pedagogical ideas about design in chemistry education also seem to have been influenced by a lack of collective pedagogical ideas, and lesson materials for design in chemistry education. Teachers regularly referred to experiences with or knowledge of design in physics educational contexts while having few chemistry-specific pedagogical ideas (for example, regarding connecting chemistry contexts or content to design activities to stimulate learning). Information available to Dutch teachers, including the design practices described in the science curriculum, are largely based on experiences with students designing in physics contexts. An absence of well-founded teaching resources hinders teachers from gaining chemistry design teaching experience, and from developing effective design lessons themselves.

Additionally, like Boesdorfer and Staude (2016) found, we saw indications of each teacher having a naïve understanding of design. And, only the teachers in the PLC with a professional background in (bio)chemical engineering (Ruben and Vera) made some references in their pedagogical ideas to design as an authentic chemistry practice. Teachers' seemingly limited knowledge of design processes, and of the role of design in chemistry might complicate translating general science, or physics-based frameworks and curriculum standards for design-based teaching to chemistry education.

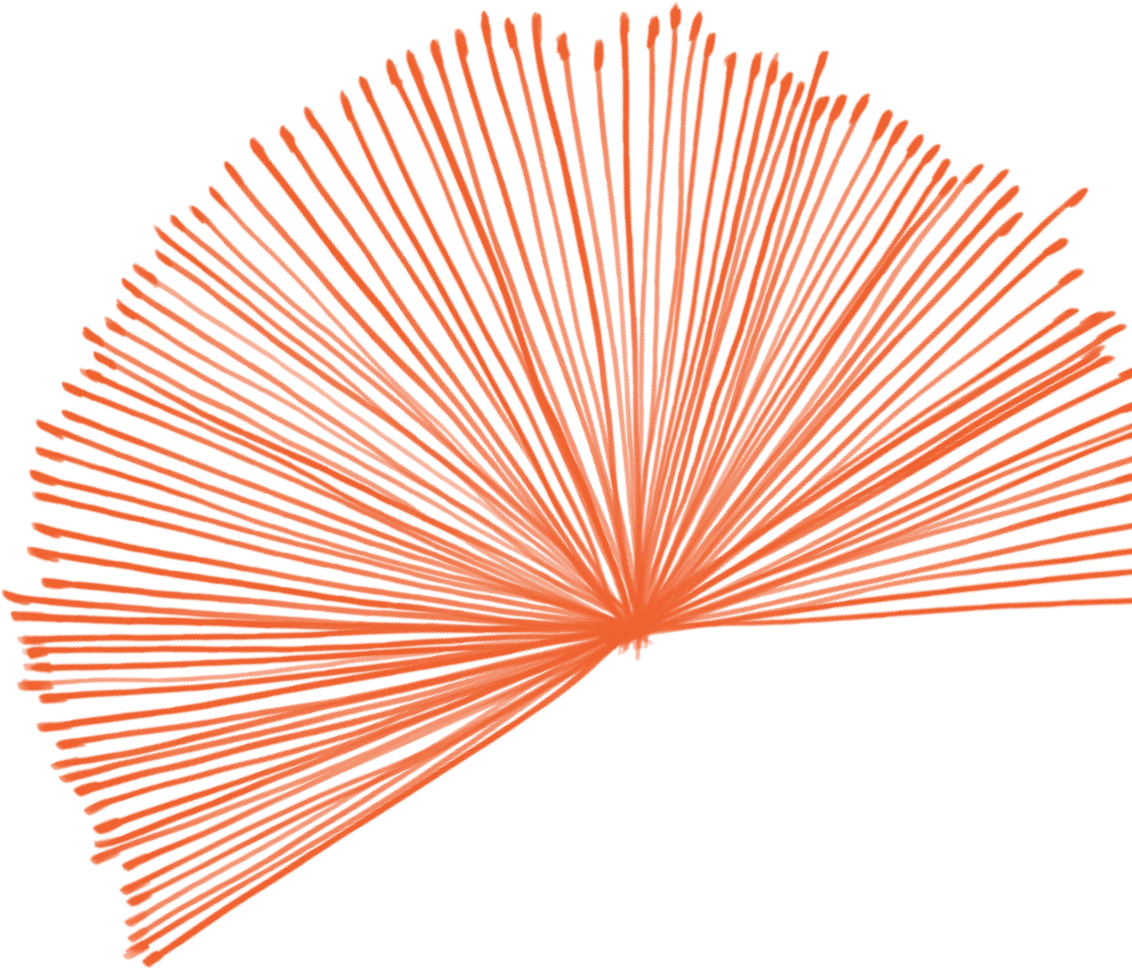
2.6 Conclusions and implications

With this study, set in the context of a Dutch professional learning community, we gained new insight in chemistry teachers' views on bringing design practices to chemistry classrooms. We conclude that, contrary to what one might expect based on design's central role in chemistry, and the Dutch curriculum reform emphasising design practices, this study's chemistry teachers did not see learning to design (in chemistry) as an important goal of chemistry education. Instead, teachers valued design as an approach to engage students in applying chemistry concepts, in developing soft skills, and in applying or developing research practices. As a teaching approach, teachers did consider design to offer benefits regarding student learning, student motivation, and preparing students for future school projects, studies and careers. But, using a design-based teaching approach in chemistry education also posed challenges for teachers, including selecting suitable design contexts that would engage students in making 'something concrete', and in applying chemistry concepts. To make teaching design in itself more relevant, teachers said to teach design as a more generally-applicable process or problem-solving approach. Although the PLC's teachers thus had multiple pedagogical ideas in common, we found ideas also varied per teacher.

Whereas bringing design to physical science classrooms is sometimes seen as a 'natural fit' (as mentioned in Roehrig et al., 2012), our findings show this connection is not necessarily explicit for chemistry teachers teaching chemistry. To develop their understanding of the role of design in chemistry, the chemistry teachers of this study, and chemistry teachers in other contexts, may benefit from professional development opportunities addressing the practical (Freire et al., 2019), technological sides (Bensaude-Vincent, 2009; De Vos et al., 2002) of chemistry. Additionally, our findings show the PLC teachers' need for support in learning to recognise (and perhaps use) opportunities to stimulate student learning in the context of design, as well as in developing practical skills to guide student learning in 'hands-on, learner-centred and project-based' contexts (as also noted by others, incl. Kolodner et al., 2003). Although some teachers had more experience regarding design (see Table 2.1), which might have influenced the extent and coherence of their pedagogical ideas, data analysis of both sources and comparisons with literature showed all teachers were at a beginning stage in their thinking about design in chemistry education, and could benefit from such support to develop pedagogical ideas about design in chemistry education. Since we found that chemistry teachers' primary goals for integrating a design-based teaching approach can vary, more chemistry teachers might be motivated to bring design practices to their classrooms by developing professional development programmes, and lesson materials which accommodate for a variety of perspectives.

The design and effect of teacher professionalisation initiatives on chemistry teachers' pedagogical ideas and their teaching are interesting topics for future research. Follow-up studies could also investigate whether the categories and patterns we found are more common among chemistry teachers, and whether chemistry teachers can hold views we did not come across in our sample (such as stimulating students' chemistry reasoning or daily-life decision making through design, or seeing teaching design as a relevant goal in chemistry education). Developing chemistry-specific principles for teaching and learning to and through design is also an important research direction. As our literature review showed, research on design in secondary school chemistry education is still scarce. And, the chemistry teachers in this study also expressed a clear need for design-based teaching strategies and lesson examples they felt they could take into their classrooms.

Studying chemistry teachers' pedagogical ideas in the context of a PLC provided us with in-depth insight in their views. Basing our data collection and analysis on the four general pedagogical elements of learning goals, student learning, instructional strategies and assessment, and collecting data through interviews as well as lesson forms allowed us to investigate the (tacit) pedagogical ideas of a group of teachers who, despite having had different experiences, were all beginning to explore the field of design in chemistry education. Other researchers aiming to explore the pedagogical ideas of teachers in an innovative educational context may also be interested in using this approach (although filling out logbook-type forms can be demanding for some teachers). Moreover, the five categories of pedagogical ideas that emerged in this study can be adopted as an initial analytic framework for future research studies.



3

Examining the multidimensionality and dynamicity of teacher attention in a design-based chemistry context

3.1 Introduction

Paying close attention to student learning in the course of instruction is increasingly considered an important facet of science teachers' expertise (e.g. Levin et al., 2009; Chan et al., 2020; Barnhart & Van Es, 2015; Cowie et al., 2018). Rosemary Russ (2018) describes how this development is motivated by theoretical and empirical work highlighting the importance of instruction eliciting students' existing understandings. Making student thinking observable and interpretable means that teachers can shape instruction in such a way that it allows students to use existing resources as a valuable foundation for developing their thinking (Russ, 2018). Researchers have similarly advocated for attending to aspects of learning such as students' research practices (Hammer et al., 2012), and design practices (Watkins et al., 2021) to better support student learning during a learning process.

Attending to student learning has been posited as particularly complex in design-based education contexts (Watkins et al., 2018). The multifaceted and open-ended nature of design challenges can lead to a particularly wide variety of student ideas for teachers to make sense of. Moreover, design-based science projects tend to target an array of learning goals (e.g. involving science ideas, research practices, collaboration, metacognition; Kolodner et al., 2003), which teachers need to navigate (Watkins et al., 2018). The reform-based character of design-based science education may further contribute to the complexity of attending to student learning. Design has only relatively recently been introduced in secondary school science curricula (e.g. Board of Tests and Examinations [CvTE], 2014; National Research Council [NRC], 2012). Science teachers may not have had much opportunity to gain practical experience with this type of education nor to develop their knowledge about design-based teaching and learning. Teachers' cognitions and classroom experiences are, however, important resources in supporting their attention to student learning (Meschede et al., 2017; Santagata & Yeh, 2016). While teacher attention has disciplinary and task-specific characteristics (e.g. Coffey et al., 2011; Talanquer et al., 2013), research into teacher attention in secondary school, design-based science contexts is still scarce.

In this work, we seek to build our understanding of teacher attention to student learning in secondary school, design-based science education by examining its multidimensionality and dynamicity. Multidimensionality refers to the range of objects of interest that teachers have when observing students and students' products (Erickson, 2011). While researchers often zoom in on specific objects of teachers' interest (e.g. students' disciplinary thinking; Richards, 2013), we take a broader view as we examine teacher attention in a design context. We draw on work describing experienced science teachers as attending to 'science, social and personal aspects of student learning' (Cowie & Bell, 1999), as we pursue specifying the breadth of aspects of student learning a teacher may attend to in a design-based science context. Dynamicity refers to the objects of teacher attention being sensitive to changes in context (e.g. differing between types of lesson activities; Russ & Luna, 2013; Lam & Chan, 2020), and possibly changing over time (e.g. in the course of a professional development program; Watkins et al., 2021). Grasping the dynamicity of teacher attention is particulary relevant in light of the reform-based character of design-based science education.

To gain insight in the multidimensionality and dynamicity of teacher attention in a design-based science context, we engaged an experienced chemistry teacher (pseudonym Joanne) in weekly reflection conversations while she implemented a design project. Teachers' reflections on classroom practice have been grabbing the interest of researchers in this field because of their potential for unveiling teachers' (tacit) objects of attention, and for supporting development of teachers' attention (Van Es & M. Sherin, 2008). We expected that provoking and analysing Joanne's reflections would provide a window into teacher attention. We had previously found Joanne to have experience with design-based (chemistry) teaching, see multiple goals for design-based chemistry education, and exhibit relatively many and well-connected pedagogical ideas in this area (Stammes et al., 2020). Moreover, Joanne was engaged in developing her attention to student learning as a member of a professional learning community on design-based chemistry education with a specific focus on formative assessment. Formative assessment centres on attention to student learning (Coffey et al., 2011).

This study's detailed examination of Joanne's attention to student learning offers empirical grounding to those who want to support communication about and development of teacher attention to student learning in design-based science contexts. This study's first-time use of a 'midstream modulation approach' to reflection conversations (Fisher, 2007; Fisher et al., 2006), furthermore provides a response to a recent call for investigating new opportunities for teacher reflection in the context of design education (Watkins et al., 2021). This study's findings additionally pose avenues for future research in the emerging area of teacher attention in design-based science education.

3.2 Background

Teachers' attention to student learning lies at the core of multiple notions on meaningful (science) education which are shaping the current educational landscape (also see Russ, 2018). These notions include formative assessment (Cowie & Bell, 1999; Black & Wiliam, 2009), teacher noticing (M. Sherin et al., 2011a; Jacobs et al., 2011), and responsive teaching (Hammer et al., 2012). While each notion offers a certain perspective on what it means to attend to student learning, many highlight the importance of teachers consulting and interpreting information on student learning in the course of instruction to inform subsequent action. This can enable teachers to adapt their actions and classroom activities to students' learning needs during a learning process (Cowie et al., 2018).

One of the goals pursued in research involving these interrelated educational notions concerns improving understanding of what teachers attend to when engaged in 'attention processes' like interpreting and responding. While some lines of research in this field have been criticised for focusing too much on domain-independent strategies for attending to student learning (Coffey et al., 2011), studying what teachers attend to allows for (sub) domain-specific characterisations (Russ, 2018). In the case of the present study, we pursue insight in objects of teacher attention in a design-based science context. To this end, we first turn to existing literature on teachers' objects of attention in science and (engineering) design education, and describe how attention to student learning can be studied.

3.2.1 Objects of attention

Multiple objects

Erickson describes finding 'tremendous variety in kinds in the differing objects of teacher attention' (2011, p. 21). In other words, teacher attention tends to be multidimensional in terms of its associated objects (Erickson, 2011). Research into science teachers' attention to student learning, nevertheless, often zooms in on attention to aspects of learning typically classified as disciplinary. That is, ways of thinking and doing that are characteristic for a certain domain of science (education). Some researchers have focussed on teachers' attention to students' science thinking (e.g. ideas about natural selection; Furtak, 2012), or scientific practices (e.g. inquiry skills; Talanquer et al., 2013). Such studies have revealed, for example, that one teacher may notice a range of chemistry ideas while interacting with students in a design-based classroom, whereas another may not (Stammes et al., 2021). Others have stressed that, while science thinking and participation in scientific practices are different educational objectives they are also related, and thus examined a teacher's attention to both (Hammer et al., 2012). More recently, researchers have also started to examine attention to students' design practices. This development is particularly evident in studies conducted at the elementary school level (see Luna et al., 2018; Watkins et al., 2018; Watkins et al., 2021; Dalvi & Wendell, 2017). But, the development does mirror that of science curricular reforms being implemented across K to 12 education. These curricula are placing more emphasis on science students' engagement in (engineering) design practices, such as problem scoping and generating design solutions (e.g. CvTE, 2014; NRC, 2012). Among reasons for an increased emphasis on design practices are supporting 'deep learning' of science concepts and scientific practices (Kolodner et al., 2003), and preparing students for scientifically literate citizenship and science and/or engineering studies and professions (e.g. NRC, 2012; Sevian & Talanquer, 2014; Apedoe et al., 2008).

Other researchers have cast a wider net when investigating what science teachers attend to. Cowie and Bell (1999) describe how a group of experienced science teachers attending to 'the whole student'. They found teachers formatively assessing science, personal and social aspects of student learning (Cowie & Bell, 1999). Other studies along this line of investigation also suggest that paying attention to one aspect of student learning may help teachers attend to another aspect. For example, Jessica Watkins and colleagues (2018) found indications of elementary teachers' attention to students' social interactions in design-based literacy lessons supporting their attention to students' budding design practices (e.g. considering multiple design solutions rather than focusing on a single idea). Similarly, Talanquer and colleagues (2013) found that prospective science teachers' noticing of 'task-general' elements, which can be noticed in any task (e.g. the completeness of student work), could guide their attention to students' inquiry skills. Not only empirical studies into teachers' attention point to the relevance of studying the breadth of aspects of student learning teachers attend to when aiming to grasp the complexity of their attention. A recently published theoretical framework, for example, advocates attending to students' cultural-disciplinary ways of thinking and participation as members of a learning community in addition to 'more traditional disciplinary' aspects of learning in order to, among other pursuits, acknowledge student diversity as a resource, and support lifelong learning (Cowie et al., 2018).

Changing objects

Previous research has furthermore highlighted that teachers' objects of attention can vary in time and between contexts. For example, researchers found that elementary teachers' attention to students' design practices shifted in the course of a graduate program (Watkins et al., 2021). For one of the teachers in this study, this shift entailed moving from a focus on seeing design as a linear, stepwise process to acknowledging the dynamic, integrated nature of design practices when attending to student learning. Dynamicity in teachers' objects of interest has also been observed between different types of classroom activities (Russ & Luna, 2013; Lam & Chan, 2020), and during a single conversation with students (Lau, 2010). For instance, a teacher was found to focus more on students' task management during moments of lab work, and on students' biological thinking during whole-class discussion (Russ & Luna, 2013).

The multiplicity and dynamicity of objects of teacher attention still remains to be examined in design-based science contexts.

3.2.2 Studying teacher attention

Reflection on classroom practice

This present study into teacher attention is situated among those investigating attention to student learning by eliciting and analysing teachers' reflections on classroom practice (e.g. Van Es & M. Sherin, 2008; Watkins et al., 2021; Barnhart & Van Es, 2015). Engaging in reflection entails making sense of practice-based experiences, and using insights to inform future actions (Korthagen & Kessels, 1999; Schön, 1983). Multiple parallels can be drawn between processes of reflection and processes of teacher attention. Van Es and M. Sherin (2008), for example, describe how frameworks for engaging teachers in reflection and those characterising teacher attention can both be found to highlight teachers’ interpretation of particular classroom events. Close examinations of teachers’ reflections can yield rich characterisations of teachers’ attention to aspects of student learning (see, for an example, Watkins et al., 2021). Teachers’ reflections are furthermore of interest to educational researchers because of the role that ongoing and systematic reflection plays in supporting teachers as reflective practitioners who seek to improve their practice (Schön, 1983). However, researchers have cautioned that framing reflection as ’self-study’ may actually prompt teachers to focus on themselves and their own behaviour instead of on students (Levin et al., 2009; Barnhart & Van Es, 2015). This study’s embedding of teacher reflection and classroom practice in a formative assessment environment (see Figure 3.1) could mediate this.

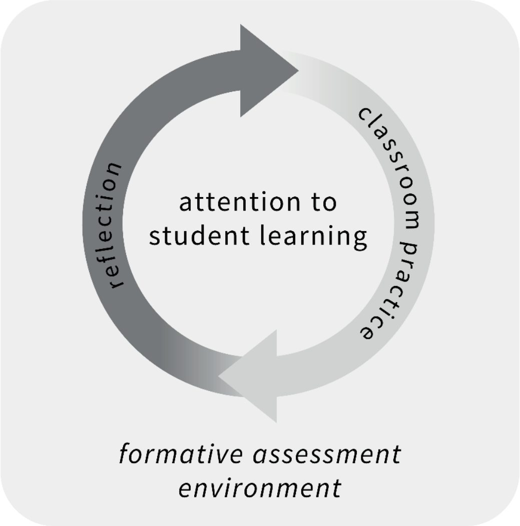


Figure 3.1. Visual overview of this study’s embedding of teacher reflection (dark grey arrow) in a formative assessment environment (grey background) in order to obtain insight in teacher attention to student learning (the middle). The two connected arrows, one for teacher reflection and one for classroom practice, highlight that reflection entails making sense of practice-based experiences, and using these insights to inform future actions.

Formative assessment environment

Formative assessment is one of the educational notions in which processes like eliciting, interpreting and acting on information about student learning are central (Black & Wiliam, 2009; Cowie & Bell, 1999). Researchers have argued that ‘the heart’ of formative assessment should be seen as ‘attention to what and how students are thinking and participating’ (Coffey et al., 2011, p. 1112). We selected a formative assessment perspective on teacher attention for this study, as the participating teacher was a voluntary member of a Professional Learning

Community on design-based chemistry education and formative assessment. What and how to formatively assess student learning in a design-based chemistry context were questions guiding the PLC's activities (including the creation, implementation and evaluation of design-based chemistry projects). In this study and our interactions with teachers, we take an inclusive view on formative assessment (in other words, on what counts as attention to student learning). We take formative assessment to encompass planned and interactive assessment processes (Cowie & Bell, 1999); processes occurring in the heat of classroom enactment (e.g. Ruiz-Primo, 2011), and during moments of deliberation (e.g. Tomanek et al., 2008); and as possibly guided by learning goals, which can be predetermined (e.g. Black & Wiliam, 2009; Ruiz-Primo, 2011), or arise unexpectedly through interactions (e.g. Cowie & Bell, 1999; Coffey et al., 2011). A formative assessment environment has been productively used before to examine teacher attention to student learning (incl. Luna & Selmer, 2021). But, whereas Luna and Selmer speak of a 'researcher-designed formative assessment space outside of the active classroom' to make a teacher's attention to student learning observable (p. 3), the formative assessment environment in this study arose from a collaboration between teachers and education researchers, united in the PLC. This study's formative assessment environment was also evident in the dialogic approach used for eliciting a teacher's reflections on classroom practice: midstream modulation.

Midstream Modulation

Researchers have advocated that engaging teachers in reflection through conversation with others is important for encouraging reflection (incl. Husu et al., 2007; Rodgers, 2002; Schön, 1988; Walsh, 2013). In this study, we make use of a 'midstream modulation' approach to reflection conversations (Fisher, 2007; Fisher et al., 2006). Midstream modulation engages participants in situated and ongoing reflection dialogue, in order to observe and stimulate reflection on practice, and support decision making for future actions (Fisher, 2007). This approach has thus far been used productively in interactions with science and engineering professionals (e.g. Fisher, 2007; Flipse et al., 2013; Smolka et al., 2020), and shares characteristics with methods used in education contexts. These characteristics included reflecting on situations from participants' practice with the aim to improve practice, a focus on collaborative inquiry, and the use of a multi-component protocol to guide reflection (also see, e.g., Korthagen, 1985; Rodgers, 2002). Midstream modulation research additionally highlights that certain novel perspectives can be amplified and introduced by the coach ('embedded researcher') during reflection conversations (Fisher, 2007; Flipse et al., 2013; Smolka et al., 2020). Whereas perspectives of interest in previous research concerned technical, societal, ethical and economic ones, we use midstream modulation for the first time in this study's education context to encourage adoption of a formative assessment perspective.

3.2.3 Research question

In this study, we seek to gain insight in the multidimensionality and dynamicity of teacher attention to student learning in a design-based science context. We examine this by engaging an experienced chemistry teacher in weekly reflection conversations during the implementation of a design-based chemistry project. The following research question guides the study:

> What aspects of student learning form the focus of an experienced chemistry teacher's attention to student learning in a design-based chemistry context, and how does attention to these aspects change in the course of a design-based chemistry project and weekly reflection conversations?

3.3 Methods

We employed qualitative research methods to examine an experienced chemistry teacher's attention to student learning in a design context. We collected data on this teacher's attention during her implementation of a design-based project for 10th-grade chemistry education.

3.3.1 The participating teacher and design-based chemistry project

The chemistry teacher participating in this study was Joanne (pseudonym). Joanne was a voluntary and active member of a Professional Learning Community (PLC) on design in chemistry education with an emphasis on formative assessment. Joanne had over 20 years of experience as a secondary school chemistry teacher, 7 years of experience as a STEM teacher (incl. teaching biomedical design), and experience with developing and implementing design projects for chemistry education (incl. projects on chemical Rube Goldberg machines, drugs and toothpaste). In the context of the PLC, which had been running for a year at the time of this study's data collection, Joanne had been involved in activities including implementing, reflecting on, and adapting design projects. She had also experimented with formative assessment in chemistry lessons, and reflected on this in PLC meetings. The present study's data collection took place as Joanne implemented the first version of The Thermo Challenge' design project that was being developed in the PLC.

In The Thermo Challenge project, 10th-grade students iteratively design a product which harnesses chemical energy to change the temperature of a drink or food item. Students work in teams, and set their own design problem within this setting (e.g. designing a product for travelling parents who want to give their baby a warm drink). The project version Joanne implemented aimed to help students apply and develop understanding of chemistry concepts (specifically reaction energy, rate and heat), and skills relevant in design-based chemistry contexts (specifically argumentation, drawing and collaboration; also see Apedoe et al., 2012; Roth, 1994; Siverling et al., 2019). The project's activities, spanning eleven lessons, were informed by the Dutch curriculum (CvTE, 2014), and Learning-By-Design approach (Kolodner et al., 2003).

Opportunities for formative assessment were incorporated throughout the project, and described in the teacher guide to encourage the teacher's attention to student learning. Suggested activities included, for example, conducting a whole-classroom discussion to establish success criteria (see Wiliam & Leahy, 2015) for argumentation and drawing in the design-based chemistry context; recurring white-boarding sessions where students formulate learning goals and lessons learned with their teacher (see Kolodner et al., 2003); and sharing design suggestions on a wall in the classroom. Workbooks and sheets for students were developed to guide students through the project's activities (e.g. problem scoping; using research results in design planning; also see Kolodner et al., 2003), as well as to offer teachers a source of information on student learning accessible in and after class (also see, e.g., Luna et al., 2018). The teacher guide described and explained formative assessment opportunities, also drawing explicit connections to the formative assessment model used in the PLC (that of Wiliam & Leahy, 2015).

Joanne implemented this design project in her 10th-grade chemistry class at a Dutch 'gymnasium' school. This university preparatory class consisted of 28 students of around 15 to 16 years old. The project ran for almost 4 weeks (3 lessons per week). Joanne was informed about the research, and gave her consent.

3.3.2 Data collection

To gain insight in Joanne's attention to student learning, we engaged her in weekly reflection conversations as she implemented the Thermo Challenge design project. We used a midstream modulation approach, where the first author took up the role of the embedded researcher (Fisher & Mahajan, 2010; Smolka, et al., 2020). During the reflection conversations, the researcher guided the conversation through the components of the midstream modulation protocol, encouraged adoption of a formative assessment perspective, and used observations as resources feeding into the conversation. We address these main, interrelated strategies in more detail next.

To provoke reflection, we used the midstream modulation protocol with its four components (opportunities, considerations, alternatives, outcomes; Fisher, 2007). We used questions from earlier studies as a basis (brought together in Fisher et al., 2016), and tailored these to our study's context. Examples of questions are: 'What stood out to you in the last lessons [opportunities]?'; 'Why did you think that to be important [considerations]?'; 'What are other ways you could try out [alternatives]?'; 'What would you prefer to do, and why [outcomes]?'. During the conversation, the researcher made notes on a piece of paper divided into four quadrants to facilitate the process of moving through the components of the protocol. The protocol was, however, not treated as a fixed, stepwise procedure, but as a fluid and iterative process in which it was important to let a conversation develop naturally (Fisher et al., 2016).

The researcher encouraged adopting a formative assessment perspective during the conversations. Questions and statements aimed to amplify or suggest this way of thinking. Examples include (with formative assessment processes shown in brackets): ‘Would you want to ask students about that [elicit information]?’; ‘Why do you think students did that [interpret information]?’; ‘Do you feel like you know what students were thinking while engaged in construction [consult, interpret information]?’; and ‘What are you planning to do when you encounter that misunderstanding [act on information]?’. The teacher’s consultation of student artefacts was encouraged. For example, asking ‘Do you still have their brainstorms somewhere?’ aimed to encourage Joanne to describe her observations with a source of student information present (also see, e.g., Luna & Selmer, 2021).

The embedded researcher furthermore used her own observations as resources to elicit and support Joanne’s reflection (Fisher & Mahajan, 2010; Smolka, et al., 2020). These observations stemmed from a variety of sources, including earlier (reflection) conversations with Joanne; observations of Joanne’s lessons (one per week); interactions with her students (specifically focus groups about students’ learning and perception of the project’s activities); discussions with fellow researchers (incl. reflections on the reflection conversations); desk research (specifically into design-based learning and formative assessment); and reflection conversations with two other teachers running parallel to Joanne’s. Using observations as resources occurred, for instance, when Joanne looked for an alternate course of action, but could not think of one.

We engaged Joanne in a total of four reflection conversations during the implementation of the design project (one conversation per week; conducted at school). Conversations were audio recorded. Conversations 1 to 3 were 44 to 56 minutes in duration. The fourth conversation took place when the project had just ended, and was shorter in duration (15 minutes). To support subsequent data analysis, we also collected secondary data. This data included field notes of observed lessons, teacher-made quizzes and presentations, student workbooks (incl. Joanne’s written feedback), and semi-structured pre/post interviews with Joanne (questions concerned formative assessment, pedagogical content knowledge and perception of the reflection conversations).

3.3.3 Data analysis

After transcribing the recorded conversations, we analysed the transcripts in three phases to characterise what aspects of student learning formed the focus of Joanne’s attention, and how her attention changed through time.

Selecting attention segments

First, we selected the segments in the transcripts that concerned attention to student learning. To identify these segments we, again, adopted a formative assessment perspective. As a provisional analysis framework, we used the formative assessment processes distinguished by Wiliam & Thompson (2008). Their formative assessment model and its more recent versions (specifically Wiliam & Leahy, 2015) had played a central role in our interactions with the PLC's teachers. While reading the transcripts and selecting fragments, we came to expand and adjust this initial framework. For example, as well as coming across segments where Joanne talked about clarifying learning goals to students (as highlighted in Wiliam & Thompson, 2008), we noticed that Joanne was talking about the identification of learning goals for students (see Table 3.1 for an example). Teachers' identification of goals has also been characterised as an essential part of formative assessment (e.g. Haug & Ødegaard, 2015; Coffey et al., 2011), and we incorporated this in our analysis framework.

Through this combined deductive and inductive analysis approach (also see Miles et al., 2013, p. 86), we ultimately came to select all segments that involved Joanne talking about: identifying and/or clarifying learning goals and/or success criteria; eliciting and/or consulting information about student learning; interpreting information about student learning; and/or, acting on information about student learning. As well as selecting segments where Joanne was the main actor of a formative assessment process, we included segments were she talked about engaging students as actors in a formative assessment process (e.g. students identifying themselves what they need to learn; students giving each other feedback; following Wiliam & Thompson, 2008). Selected responses could concern processes already implemented (e.g. when Joanne talked about having shared a learning goal with students in a past lesson), taking place during a reflection conversation (e.g. when Joanne discusses student workbooks which she consults during the conversation), and getting planned (e.g. when Joanne considers what eliciting questions to ask students in the next lesson). We did not select segments revolving around a summative assessment purpose (i.e. assessing student learning at the end of a learning process rather than during). In Table 3.1 we present two examples of segments and their evaluation against the selection criteria.

Coding aspects of student learning

With the segments selected, we proceeded to identifying and coding the aspects of student learning Joanne focussed on. This meant turning our analytic efforts to the objects of the attention processes (e.g. what learning goal did she say to have clarified in class; what information about student learning does she plan to elicit; etc.). Again, the analysis approach had both deductive and inductive characteristics as we sought to create codes with both theoretical and empirical relevance. Our initial coding was informed by Cowie and Bell's (1999) finding that teachers attended to science, social and personal aspects of learning, as well a previous characterisation of chemistry teachers' pedagogical ideas (Stammes et al., 2020). During analysis, we specified initial codes and created new codes to account for our observations in this study's data. We referred to other works to aid interpretation of data and

Table 3.1. Examples of reflection conversation segments, and their evaluation against selection criteria.

Example segments	Evaluation against selection criteria
‘You can let them draw such an [energy] diagram, like what suits the reaction that you choose. That is the exercise they get. And, in principle that fits fine. But, if you provide a wrong answer to that question, it has no consequences for the rest of the design process. So, it’s not as if it cannot be connected to the story, but it’s not truly part of the design process. And that’s just what I like about when you really start making calculations for it [the design], with the ‘delta T’ etcetera. Then you are really able to say: “Yes, that formula, I don’t just have to learn it for a test, but it comes in handy now because then I can estimate beforehand, if I want to heat up 150 millilitres instead of 5 millilitres, how much more energy, what do I then need to do to get the right amount of energy for that”.’ (conv. 1)	This segment met the selection criteria as it concerns Joanne talking about identifying learning goals (comparing the relevance of two goals). The response was thus selected for further analysis.
‘I think that most of them are focused more at this moment on energy than rate, because I got a question yesterday from a group, like “mam, how warm is a cup of warm chocolate milk actually when it’s nice, and you want to drink it?”. I say, “yes, that’s a good question”. But, then you notice that they are thinking about how to achieve that temperature. That’s the first thing they are engaged in, and I do think that is indeed logical, because that is your starting point of course, it needs to get hot or cold enough. And, next you can refine that. Like, is it also going fast enough, does it stay at that temperature long enough? Those are follow-up questions. So, considering that, I think that that sequence makes sense, addressing energy first, and reaction rate at a later stage.’ (conv. 1)	This segment met the selection criteria as it concerns Joanne talking about consulting information about student learning (students having asked her a question), interpreting information about student learning (inferring students’ thinking; determining how that thinking makes sense), and acting on information about student learning (responding to students’ question; reconsidering the sequence of the project’s lessons). The response was thus selected for further analysis.

definition of codes. In addition to the works already referenced in this paper (incl. Hammer et al., 2012; Talanquer et al., 2013; Luna et al., 2018; Watkins et al., 2018), we also turned to other studies to facilitate this process (incl. Heredia et al., 2021; Kelly & Cunningham, 2019; NRC, 2005; Zhang et al., 2020).

We ultimately developed seven codes describing Joanne's attention to aspects of student learning, namely attention to students' chemical thinking, design practices, research practices, social interactions, ownership, emotions, and behaviour. Table 3.2 presents these codes with descriptions, and examples from data. One segment could receive multiple codes. The first example segment provided in Table 3.1, for instance, concerned Joanne talking about learning goals involving students' chemical thinking (concerning energy diagrams and the energy transfer formula), and engagement in design practices (design in general and design planning specifically). As well as applying the seven major codes to the selected segments, we used in vivo coding to help capture Joanne's objects of attention within an aspect of learning. Examples of these subcodes included, for instance, 'energy diagram quiz', 'did not consider amount of substances', 'knowledge required to understand', 'busy calculating' and 'theory already addressed' regarding attention to students' chemical thinking.

Characterising attention through time

Lastly, we looked for patterns in the coded data that described Joanne's attention to each of the identified aspects of student learning over the course of the design-based chemistry project and reflection conversations. Per reflection conversation, we examined which aspects Joanne focused on (e.g. was students' chemical thinking an aspect of interest?), as well as what Joanne focused on within each aspect of student learning (i.e. sub aspects of learning; e.g. what kind(s) of chemical thinking did she focus on?). To help us find and verify patterns (also see Miles et al., 2013), we referred to analytic memo's written during previous analysis phases, looked for counter examples, calculated and plotted code frequencies, consulted secondary data sources (incl. post interviews and field notes), and discussed emerging patterns within the research team. In the findings section, we present our characterisations of Joanne's attention to student learning over time for each of the seven identified aspects.

Table 3.2. Codebook for the aspects of student learning forming the focus of Joanne's attention processes.

Aspects of student learning	**Description**	**Examples from data**
Chemical thinking	Statements concerning students' chemistry ideas, reasoning, work with formula etc.	'[…] There was a group of students who said – they had indeed been calculating something, I did not check whether they calculated it correctly, but that could be - they said "Mam, we actually need ten times as much energy", and I said "How can you fix that?", "Well, do we then need ten times the amount of chemicals?", and I say "Well, maybe you indeed need to think in that direction" […]' (conv. 2)
Design practices	Statements concerning students' design ideas, reasoning, practices, activities, products etc.	'But there were quite few [students] who really made substantial changes in their drawing. They are looking more at, well amounts. For some I did see that they, for example, clearly changed the ratio between the compartment where the reaction takes place, and the drink itself, so to say. Or, they elongated the cup. Well, they used all sorts of tricks to expand the contact surface, and to fit in more of the substance […]' (conv. 4)
Research practices	Statements concerning students' research ideas, reasoning, practices, activities, products etc.	'Look, it has actually warmed up quite a bit already. And, I don't know if I can find a good example of the.. Here there's one, they have apparently chosen a different scale regarding the minutes. Well, apparently they haven't conducted the experiment further than three minutes […]' (conv. 1)
Social interaction	Statements concerning students' interactions with others (e.g. collaboration, learning from each other)	'[…] they did want to discuss with each other, some of them just put them [design drawings] next to each other, they did not swap them, but started to more or less compare them. And they really did talk about that, so in that sense it sort of met the goal that they at least would discuss with each other, but well.. I did not get the impression that they made much progress really. I think that was sort of the problem, that they just didn't know anymore what else. […]' (conv. 3)
Ownership	Statements concerning students' ownership over and influence on learning, activities and practical outcomes (e.g. design solution)	'I also write comments on it, so for those guys I write "What a pity that so little has appeared on paper, try to catch up". But, in the end, they are the ones who need to do it. And, maybe when they have to start building and testing in a little bit that they realise like, this isn't bringing us anywhere, that messing around. That might very well happen. […]' (conv. 1)

Table 3.2 continued

Behaviour	Statements concerning students' general behaviour during lesson activities or products of this behaviour	'Well, those groups next to the window, and that group near my desk, those are working rather well […]' (conv. 3); '[…] I am really going to check whether they have produced anything […]' (conv. 3)
Emotions	Statements concerning students' emotions (e.g. excitement, anxiety, interest)	'[…] but, at the moment that they can really start thinking about: what will we choose? Well, most of them really like that […]' (conv. 1); '[…] then you could refer them to that at the moment you notice, oo now they are starting to look very sad […]' (conv. 2)

3.4 Findings

Through analysis of the four reflection conversations we identified seven major aspects of student learning forming the focus on Joanne's attention processes. These aspects of student learning were students' chemical thinking, design practices, research practices, social interactions, ownership, behaviour and emotion (also see Table 3.2). Joanne attended to these seven aspects of student learning in each reflection conversation. Students' chemical thinking and design practices formed the substance of Joanne's attention most often.

Examining what Joanne attended to within each aspect of student learning (i.e. sub aspects) showed that Joanne's attention to some aspects varied in the course of the design project and reflection conversations. This concerned her attention to students' chemical thinking, design practices, behaviour and emotions. Joanne's attention to students' research practices, social interactions and ownership, on the other hand, was more stable over time. We describe Joanne's (changing) attention to student learning per aspect of learning in detail in the following paragraphs.

3.4.1 Chemical thinking

In the first reflection conversation, Joanne said that she had told students that they were to 'learn several chemistry things'. Not only because students had a summative test coming up, but also because some chemistry topics were relevant in light of the design challenge. However, according to Joanne, this was not the case for every chemistry topic addressed in the project's lesson materials:

> You can let them draw such an [energy] diagram, like what [diagram] suits the reaction that you choose. That is the exercise they get. And, in principle that fits fine. But, if you provide a wrong answer to that question, it has no consequences for the rest of the design process.

> So, it’s not as if it cannot be connected to the story, but it’s not truly part of the design process.

Joanne did address the topic energy diagrams by assigning reading material and a quiz as homework (conv. 1). However, she discovered that students made ‘many mistakes’ in the quiz or had not done it at all (conv. 2). Joanne decided to remind students of their homework, but also to leave time to ‘set it right’ during the ‘normal’ lessons after the design project (conv. 2). While Joanne’s attention to students’ understanding of energy diagrams decreased in time, her attention to students’ understanding and use of the energy transfer formula ($Q=mc\Delta T$) increased. Joanne said that this formula could be better linked to students’ design process, as students actually measured temperature change when testing their prototype (conv. 1). Moreover, she had noticed through observing and conversing with students engaged in constructing and testing their first prototypes, that not all students were using the idea that changing the temperature of a bigger volume of drink required a larger amount of starting substances (conv. 2). In the subsequent lessons, Joanne sought to help students understand and use this idea by, for instance, asking students to write down the formula, and reply to questions like ‘So, how can you increase ΔT?’ (conv. 3). Although Joanne also referred to student thinking about other chemical concepts (particularly properties of matter and reaction rate), this thinking did not grab her interest as much. She said, for instance, to believe that changing materials – which she repeatedly found students to think about – would do little to achieve a larger temperature change compared to changing drink-to-substance ratios (conv. 3). Over time, Joanne’s attention to students’ learning of ‘chemistry things’ came to concentrate heavily on students’ understanding and use of the energy transfer formula.

3.4.2 Design practices

Joanne also said to have told her students in the beginning of the project that they were ‘to learn to design’ (conv. 1). Joanne’s attention to students’ design practices involved a wide range of practices, including setting design requirements, making choices, drawing designs, constructing prototypes, and improving designs. She often attended to students’ level of engagement in such a design practice, and whether this helped students develop a successful design solution. Joanne said, for example, to have noticed during a construction and test lesson that some students had quickly started tinkering, and had conducted multiple tests, while others had not achieved much (conv. 2). Regarding some design practices, Joanne attended to specifics in students’ budding design expertise. Concerning drawing designs, for example, she checked whether students were improving their design solution and annotating their drawing rather than merely making a pretty or colourful drawing (conv. 4). Joanne also attended to the extent to which students were ‘really thinking’ (conv. 3) when engaged in a design practice. For instance, having observed a student placing insulation material between the reaction and drink compartments of his prototype led Joanne to conclude that the student ‘had not been thinking’ (conv. 2).

A more specific type of ‘really thinking’ which Joanne increasingly zoomed in on in the course of the data collection, was whether students were considering ‘ratio’ when designing. With ratio she meant the ratio between the amount of starting substances and volume of drink to be changed in temperature (also see the chemical thinking section). Joanne referred, for example, to this during the second conversation in her reflections on a construction and test lesson:

> There was a group, they really had such a [large] glass beaker, and in it they had, I believe, almost one litre of water. And, they had put something in that should heat up or cool down that whole business. Then you just know that that is not going to happen, hahaha. On a different, smaller scale, however, more thought through…

Over time, Joanne came to see students using this idea as the key to developing a successful design solution. She noticed again and again that many students were not incorporating this idea in their designs (convs. 2, 3). Joanne subsequently sought to stimulate students to change ratios through conducting various follow-up actions including having the lab assistant set out larger quantities of substances, asking students questions and giving concrete suggestions (convs. 2, 3, 4). Joanne also came to look more deliberately for evidence of students thinking about ratios, consulting a variety of sources of information (incl. students’ design drawings, prototypes, verbal expressions, test results; convs. 2, 3, 4). In the last reflection conversation, she could finally remark that ‘some students had clearly changed the ratio between the space where the reaction takes place and the cup containing the drink’.

3.4.3 Research practices

From the start onwards, Joanne’s attention to students’ research practices took shape as attending to students’ ‘measurement taking’. This specifically involved students’ temperature measurements during investigatory lab activities and prototype tests. Joanne’s remarks often involved the change in temperature students measured, such as during the first conversation:

> […] yesterday I quickly scanned through all graphs, and I saw in all of them that a maximum or minimum had appeared. […] This graph goes from 19 to 70 [degrees], this one to 60, 65.

Joanne additionally considered occasionally whether or how students were taking measurements (e.g. ‘doing the tests one after another instead of at the same time’; conv. 1), whether or how students were documenting measurements (e.g. they have chosen a different time scale; conv. 2), and students’ measurement expectations (e.g. ‘of course the measurement does not go as they expected’; conv. 2). Based on her observations, Joanne described taking actions to help students achieve larger temperature changes (e.g. through suggesting the use of more starting substances).

3.4.4 Social interactions

Based on a whole-classroom discussion on success criteria for collaboration, Joanne had concluded early on in the project that students ‘knew quite a lot about working together’ (conv. 1). In future, she would rather give students some suggestions of her own on what to be mindful of when collaborating (conv. 1). As in this example, we found more instances in Joanne’s attention to students’ social interactions where she placed little value on students as learning resources for each other. For instance, she commented that a peer feedback activity involving students’ design drawings did not result in much progress because she had not heard students giving each other suggestions like using a larger amount of starting substances (conv. 3). Again, she planned to give students some pointers herself instead (conv. 3). There were also a few contrasting examples, though, instances where Joanne did attend to student interactions from a perspective of seeing students as learning resources for each other. For instance, she said to have told students who were insecure about their design plan that they could ‘learn from what they had heard from others’ (conv. 4). Regarding attention to students’ social interactions, Joanne also occasionally remarked on group composition and roles (e.g. ‘there are those taking initiative and the following types’; conv. 2), and students’ influence on each other’s behaviour and emotions (e.g. ‘they are influencing each other with that ‘cool guy’ behaviour’; conv. 2).

3.4.5 Ownership

Joanne’s comments concerning students’ ownership continuously revolved around students’ ‘adoption of an active attitude’ during the design project (phrase from conv. 3). To Joanne, this meant that it was students’ responsibility to, for example, ask her questions if they did not understand something, neatly complete the tasks she assigned, and take the design challenge seriously even though they would not receive a grade (convs. 1-4). However, observing and interacting with students in class, and checking students’ products (e.g. workbook assignments), repeatedly led her to conclude that not all students were taking up these responsibilities during the project (convs. 1-3). Perhaps, Joanne said, this could be traced back to a school-wide culture (conv. 3):

> Maybe the problem is that we are creating, here at school, the type of students who are too much like consumers [...] So, the student leans back, opens its mouth, and the teacher stuffs everything in. Something like that. Well, that is not an option with these kinds of projects.

To encourage students to take ownership over their learning and actions, Joanne tried ‘kicking’ students (e.g. by writing in students’ workbooks that they needed to complete exercises; conv. 1). She also hoped that getting confronted with their own design idea failing and other students' designs working successfully could make students reconsider their own attitude (conv. 1). While Joanne found that these tactics were not really improving the situation (convs. 1-4), giving students more freedom, such as in choosing which criteria for assignments they wanted to adhere to, did appear to help (conv. 4).

3.4.6 Behaviour

Joanne's attention to students' behaviour involved attending to students' on-/off-task behaviour, and the general quality or completion of tangible products of students' behaviour. For example, while looking through student groups' workbooks during the second conversation, Joanne remarked:

> I was a little bit disappointed by this group, because earlier they had been nicely engaged in drawing and were working well, like brainstorming and so. And, now they suddenly bring forth little. I don't know why honestly.

Joanne often zoomed in on the more negative examples of student behaviour. She talked in particular about those student groups where she had noticed off-task behaviour and/or lacking products (e.g. a couple of groups were giggling and chatting instead of putting something on paper; conv. 1). Also, comments about students who were behaving well were repeatedly followed by remarks diminishing the value of these more positive situations (e.g. that group is working quite nicely, but even they barely adapted their design drawing; conv. 3).

Her attention to negative facets in student behaviour, as well as her 'frustration' about this, had become particularly high at the time of the third reflection conversation. For example, despite having acted angry and friendly, and asking students whether they needed help, she said to have still found a group of students having achieved nothing when checking in on them a few minutes later (conv. 3). Having subsequently considered immediately terminating the project (conv. 3), Joanne ultimately decided to give students the opportunity to construct and test their designs one last time (convs. 3, 4). In the final reflection conversation, students' (negative) behaviour was suddenly not a major focus of Joanne anymore. Then, she only mentioned how a good-working student group had neatly completed an assignment (conv. 4).

3.4.7 Emotions

Joanne's attention to students' emotions centred on whether students were enjoying themselves during lesson activities. She had expected students, particularly the more lazy types, to have fun as they would be trying to learn by 'doing something different, with lots of practical stuff' (conv. 3). Moreover, students could 'give it their own twist', since she was not prescribing what the to-be-designed cup should look like (conv. 3). Joanne did notice students enjoying, for example, choosing their own design situation (conv. 1), and thinking of ways to improve their design (conv. 2). However, she had also observed that many students were not enjoying activities like a whole-classroom discussion about collaboration (conv. 1), and drawing yet another version of their design (conv. 4). Students also got disappointed and frustrated with their first prototypes if the temperature of their drink changed only a little bit (convs. 2, 3).

Joanne found classroom moral to be especially low at the time of the third reflection conversation (also see the section on students' behaviour). But, she hoped to still wrap up the project with a 'positive experience' for students by suggesting students to change their substance-to-drink ratios, and giving a final opportunity to construct and test their design (conv. 3). In the last reflection conversation, Joanne was relieved to have found that constructing and measuring a larger temperature change during that final test had indeed been satisfying for students (conv. 4). She subsequently remarked: 'They were happy, so I was happy'.

3.5 Conclusions and discussion

Design-based science education is known for its potential to promote a range of aspects of student learning (Kolodner et al., 2003). Leveraging the potential of this rich learning context does, however, require teachers to attend to student learning in the course of instruction (Watkins et al., 2018). This study pursued insight in the nature of teacher attention in a design-based science context by examining the multidimensionality and dynamicity of the objects of an experienced chemistry teacher's attention as she implemented a design-based chemistry project and engaged in weekly reflection conversations. We embedded the study in a formative assessment environment, and made use of a 'midstream modulation' approach to reflection conversations (Fisher, 2007; Fisher et al., 2006). In the following paragraphs we draw conclusions regarding the multidimensionality and dynamicity of teacher attention, and discuss this study's contributions, limitations and directions for future research.

3.5.1 Multidimensional attention

By closely examining Joanne's reflections we could identify seven aspects of student learning forming the centre of her attention. We found Joanne attending to aspects of student learning typically classified as disciplinary (chemical thinking, design practices and research practices), as well as to students' social interactions, ownership, behaviour and emotions. Aspects within this second set can have discipline-specific characteristics (e.g. having ownership over design problems, solutions and knowledge construction; Apedoe et al., 2008; Kelly & Cunningham, 2019), but are also deemed relevant across education contexts (see, for example, Black & Wiliam, 2009; NRC, 2005). This study's identification of aspects offers a first, empirically-founded specification of what attending to science, personal and social aspects of learning (Cowie & Bell, 1999) can entail in design-based science education. The findings furthermore demonstrate that attending to student learning in design-based science context not only means that teachers need to navigate different disciplinary aspects of learning (as highlighted by Watkins et al., 2018, p. 566). Rather, they point to the importance of adopting a multidimensional perspective on teacher attention (Erickson, 2011) when aiming to grasp teachers' attention in design-based science contexts in its complexity.

Some perspectives on formative assessment have been criticised for 'neglect[ing] the full scope of information that can be interesting and useful to teachers in practice (such as engagement)' (Shapiro & Wardrip, 2019, p. 25). The present study provides a counter example, where a formative assessment perspective did provide insight into the range of a teacher's objects of interests. We adopted an inclusive view on formative assessment processes (e.g. as encompassing both planned and interactive assessment; Cowie & Bell, 1999) when eliciting and analysing teacher reflection. This approach yielded a window into the multidimensionality of teacher attention in the novel context of design-based chemistry education.

3.5.2 Dynamic attention

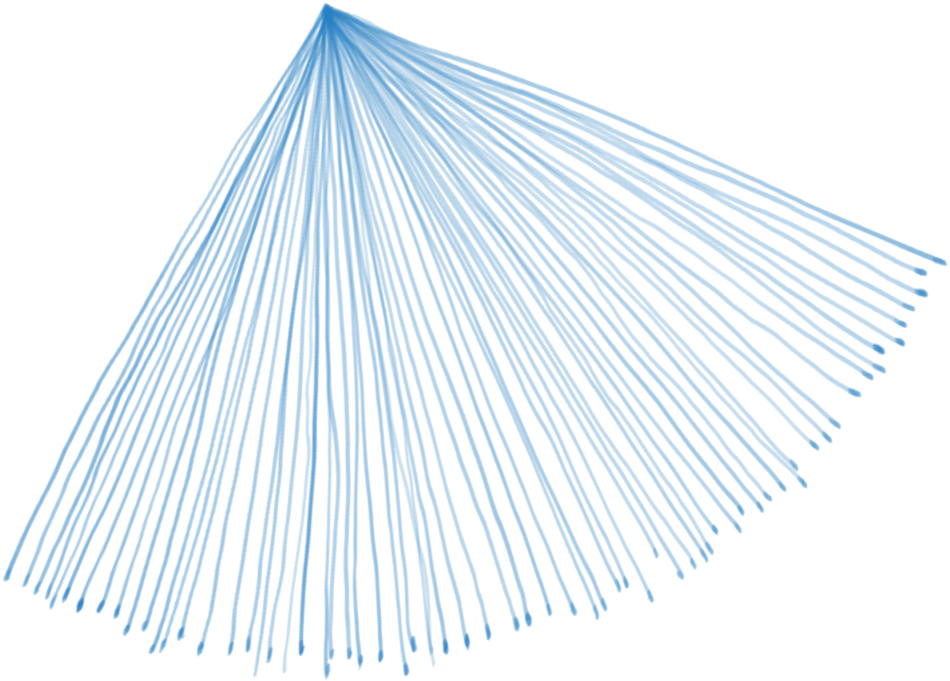
This study also examined Joanne's attention to student learning within the characterised aspects of student learning. While some investigate teacher attention at large grain sizes (e.g. whether teachers attend to students' disciplinary thinking; Van Es & M. Sherin, 2008), studying attention at finer grain sizes can provide more insight into the dynamic nature of teacher attention (Richards, 2013). Using this approach in the present study revealed changes in the objects of Joanne's attention over time, namely over the course of the implemented design project and reflection conversations. The teacher's attention to students' chemical thinking and design practices became more focused as she progressively zoomed into a particular sub aspects of student learning. Her attention to students' behaviour and emotions could be characterised as fluctuating; gaining a more negative emphasis up to the third reflection conversation, and ending with positive notes in the last conversation. Contrastingly, we observed Joanne's attention to students' research practices, social interactions and ownership to be more consistent through time. These findings provide further evidence of the dynamicity of teachers' attention to student learning (also see Watkins et al., 2021), and demonstrate that this dynamicity may be observed in the context of weekly reflection conversations accompanying the classroom implementation of a new project. Moreover, the findings show that a teacher's attention to different aspects of student learning can show different patterns of variation, in our case converging and fluctuating attention.

There are multiple possible explanations for finding variation or no variation in Joanne's attention to certain aspects of student learning. For example, Watkins and colleagues (2021) describe that teachers can develop productive stabilities in their attention to student learning over time. Perhaps Joanne (implicitly) saw her attention to certain aspects of student learning as productive or important for student learning in the design context (e.g. focussing on measurement taking in the case of students' research practices). Encountering dynamicity in what Joanne attended to may be explained by factors including her attention to student learning itself (e.g. how teachers respond shapes the new information they can make sense of; M. Sherin et al., 2011a), and what students reveal during interactions with their teacher. This study's research setting with its emphasis on teacher reflection and formative assessment may have also contributed to Joanne's attention changing over time. For example, a key attribute of the midstream modulation approach that we used is that it facilitates ongoing conversation between a practitioner and researcher over a timespan of multiple weeks (e.g. 12 or 3 weeks; Fisher, 2007; Flipse & van de Loo, 2018). Reflections from previous conversations, such as certain considerations or plans for action, form resources feeding into new conversations. This strategy appears to have facilitated tracking of Joanne's attention to the various aspects of student learning, making changes in her attention observable. Moreover, midstream modulation was originally developed not only to observe practitioner's reflection on practice, but also to enhance reflection and even improve practice (e.g. Fisher, 2007; Flipse et al., 2013). In the course of this study's data collection, Joanne may have changed, for instance, what type of information on student learning she elicited and consulted, and/or how she interpreted such information, possibly leading to changes in her attention.

3.5.3 Limitations and directions for future research

The exploratory study reported here has provided insight into the multidimensionality and dynamicity of teacher attention in a design-based chemistry education context. The findings are, however, framed by our specific research context. Future research could investigate how teachers' attention to aspects of student learning as elicited through reflection on practice compares to teachers' attention amidst classroom practice (see Russ & Luna, 2013 and M. Sherin et al., 2011b for examples of practice-based studies). Follow-up studies could also use the present study's approach in other design-based science contexts (such as design-based biology education), and with different teachers (e.g. novice science teachers), and compare findings. To gain some first insight into the transferability of this study's findings we did analyse a second set of data involving another of the PLC's teacher (6 years of chemistry teaching experience). We observed that the seven identified aspects of student learning could again be used to code and make sense of this teacher's attention. Other studies might, however, find teachers paying attention to a wider or more narrow range of aspects of student learning in design contexts. For example, teachers involved in professional development programs guided by frames like those proposed by Cowie and colleagues (2018), or implemented by Heredia and colleagues (2021), might also be found to attend to students' cultural learning (e.g. resources students bring to class from their homes and communities).

Based on this study’s findings, we would like to expand an earlier call for research into teacher attention in design-based science contexts to include not just attention to ‘disciplinary aspects of student thinking’ (Watkins et al., 2018, p. 566), but also include other aspects of student learning (incl. design practices, social interactions, and emotion). In addition to further investigating the breadth of teachers’ attention, research should examine its depth (i.e. attention within an aspect of student learning), and development. Such research may require the support of frameworks describing ‘desired’ shifts in teachers’ attention. Outlines for such frameworks are beginning to emerge in literature, highlighting, for instance, the importance of taking an interpretative stance towards students’ disciplinary thinking (Dini et al., 2020), and a nuanced view on students’ design process (Watkins et al., 2021). Developing our understanding of (supporting) teachers connecting aspects of student learning in their attention is also of importance in contexts like design-based science education with its typical multitude of learning goals. Attending to some aspects of student learning may support a teacher’s attention to another (disciplinary) aspect (e.g. Talanquer et al., 2013; Watkins et al., 2021; Hammer et al., 2012). But, having multiple foci of interest can also compete for a teacher’s attention (Richards, 2013), which we also observed Joanne to struggle with on occasion. Lastly, this study’s first-time, productive use of a midstream modulation approach (Fisher, 2007) in an educational context invites future research into the affordances and mechanisms of this approach when used with teachers as opposed to scientists and engineers.



4

Teachers’ in-the-moment noticing of students’ chemical thinking during design planning and drawing activities

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4.1 Introduction

Researchers have been emphasising the importance of teachers paying attention to student thinking as it unfolds in class (Levin et al., 2009; Coffey et al., 2011; Cowie et al., 2018). Students come to class with a range of ideas about the world around them, ideas which may not have been anticipated by teachers and lesson plans (Hammer et al., 2012). Noticing student thinking in class can enable teachers to adapt or build instruction based on students' ideas and reasoning, and tailor their actions to students' learning needs (Hammer et al., 2012; Cowie et al., 2018). These notions are also relevant in design-based science classrooms, where students are engaged in designing solutions for real-world problems.

Actively engaging students in design has been gaining traction in science education with the consolidation of (engineering) design practices in science curricular reforms (e.g. NGSS Lead States [NGSS], 2013; Board of Tests and Examinations [CvTE], 2014). In frameworks for design-based science education (incl. Kolodner et al., 2003; Fortus et al., 2004; Chusinkunawut et al., 2020), we find various ways for students to share their thinking with teachers. When students share their thinking with teachers, student thinking can become observable meaning that teachers have an opportunity to notice it (Luna et al., 2018). In 'whiteboarding sessions', for example, students are encouraged to discuss design discoveries and questions with the class, during which teachers can 'identify student misunderstanding and misconceptions' (Kolodner et al., 2003). But, while researchers may be able to identify students' disciplinary thinking while students design (e.g. English et al., 2017; Siverling et al., 2019; Chusinkunawut et al., 2020), there exists little empirical research on science teachers' noticing of student thinking during design-based activities. There have, however, been calls for investigating teachers' attention to student thinking in design-based science classrooms (Watkins et al., 2018). Design projects for science education typically target several disciplinary goals, such as goals concerning students' design practices, scientific practices and understanding of science concepts (e.g. Kolodner et al., 2003; Fortus et al., 2004; Berland et al., 2014; Guzey et al., 2017). Studying teachers' noticing of and responding to student thinking during design-based science activities may provide insight in teachers' navigation of these goals while student thinking unfolds in class (Watkins et al., 2018).

In this exploratory study, we draw on the construct of teacher noticing (M. Sherin et al., 2011a) to begin to unpack teachers' attention to student thinking during design-based science activities. We will focus our study specifically on teachers' in-the-moment noticing of students' chemical thinking during conversations with student teams who are engaged in design planning and drawing. While designing in chemistry classrooms can serve multiple purposes, it is often highlighted as a meaningful context for students to develop their ideas and reasoning about chemistry concepts (Fortus et al., 2004; Apedoe et al., 2008; Meijer et al., 2009; Sevian & Talanquer, 2014). Research suggests that students' thinking about science concepts may become observable during conversations between teachers and students surrounding students' design plans and drawings (e.g. Roth, 1994; Guzey & Aranda, 2017). As we explore teachers' noticing of students' chemical thinking in this setting, we will also investigate teachers' use of sources of evidence. Although using evidence of student thinking is often seen as an important, or even crucial aspect of teacher noticing (e.g. Santagata, 2011; Barnhart & Van Es, 2015; Lam & Chan, 2020), this remains to be explored in design-based classrooms. Design activities can, however, offer science teachers access to a particularly varied and perhaps unusual collection of potential sources of evidence, as physical artefacts like prototypes and design drawings play a key role in design processes. And, annotated design drawings, for instance, may provide insight in students' thinking about science concepts (e.g. English et al., 2017; Kelley & Sung, 2017). With the insights from this exploratory study, we aim to contribute to the growing knowledge base on teacher noticing in science education. We will additionally provide suggestions for future research and analytical instruments.

4.2 Background

4.2.1 Noticing student thinking

During instruction, teachers are faced with a 'blooming, buzzing confusion of sensory data' (M. Sherin et al., 2011a). Teacher noticing refers to the processes through which teachers manage this information overload. Teachers choose where to focus their attention on and where their attention is not needed, and interpret what they pay attention to (M. Sherin et al., 2011a). Teachers tend to have diverse objects of interest in what they see and hear students doing, such as those having to do with students' subject matter learning, effort, and emotional well-being (Erickson, 2011). While teachers may notice a range of things in a classroom, these can differ in type for different instructional activities (Russ & Luna, 2013). Researchers found, for example, that a biology teacher's noticing centred more on the substance of students' biology thinking (e.g. understanding of protein structure) during whole-classroom discussion, and on students' task management (e.g. following of standard procedures) during lab work (Russ & Luna, 2013).

While design activities are also making their way into science classrooms due to curricular reforms (incl. NGSS, 2013; CvTE, 2014), we know little about science teachers' noticing in this instructional context. Researchers have noted, however, that open-ended and multi-faceted design challenges may make noticing as well as responding to student thinking more complex, as such challenges can result in an increased variety of student ideas (Watkins et al., 2018). For instance, when generating and justifying design ideas it is likely that students consider the properties of materials even when that concept is not an explicit part of a design project's learning goals (Siverling et al., 2019). The findings of a video-based study, conducted in an elementary engineering design context, indicated that some teachers may notice student thinking about a greater variety of science concepts than others. Dalvi and Wendell (2017) asked teachers what science ideas two fourth-grade students expressed who were discussing their design for a device that could lift a giant peach out of the ocean. They found that more of the study's teachers addressed students' ideas about the concept of levers than about more abstract concepts such as weight and gravity (Dalvi & Wendell, 2017).

In this study, we explore teachers' noticing of students' chemical thinking during design activities in the authenticity of teachers' own, secondary school classrooms. Noticing students' ideas and reasoning as it unfolds in science classrooms can enable teachers to make in-the-moment decisions that help students progress towards disciplinary practices and understandings (Hammer et al., 2012). As teachers may thus be faced with diverse thinking in design contexts, we are particularly interested in characterising teachers' noticing of students' chemical thinking (i.e. ideas and reasoning about chemistry concepts) in terms of the range of involved chemistry concepts.

Although teacher noticing has been gaining research interest across educational contexts in the last decade, it is still an emerging construct which researchers conceptualise in different ways (Jacobs, 2017). For instance, whereas some researchers have investigated teacher noticing processes separately, others have studied teacher noticing holistically (Thomas, 2017; Walkoe et al., 2019). Teacher noticing is often taken to involve at least the two main processes of attending and interpreting, but the relationship between these processes is dynamic and complex (M. Sherin et al., 2011a; M. Sherin, 2017). Researchers have raised both theoretical (e.g. perception being both a top-down and bottom-up process) and practical questions (e.g. unclear where attention stops and interpretation begins) regarding disaggregation of these processes (B. Sherin & Star, 2011; M. Sherin, 2017; Superfine et al., 2017). In this exploratory study, we will take a holistic view on teacher noticing, without trying to tease apart teachers' attention to and interpretation of student thinking. This approach, which tends to place relatively more emphasis on the interpretation aspect of teacher noticing, has already shown to be fruitful in other studies with a similar research interest in teachers becoming aware of students' disciplinary thinking in science and engineering classrooms (incl. Johnson et al., 2017; Dini et al., 2020).

4.2.2 Using evidence in noticing student thinking

In classroom situations, teachers may simultaneously hear students talk, see things written on the blackboard, and more (B. Sherin & Star, 2011). The information which regards 'observable student behaviours' can provide evidence of a student's thinking (Griffin et al., 2010). This evidence can come from a variety of sources, such as from what students say, write, draw and make (Griffin et al., 2010; Ruiz-Primo, 2011). Research suggests that what teachers, and novices especially, use as evidence may not actually allow them to make meaningful inferences about student thinking (Erickson, 2011; Barnhart & Van Es, 2015). Teachers can, for example, see students' enthusiasm in raising their hands and on-task behaviour as evidence of students having achieved a lesson's learning goals (Barnhart & Van Es, 2015).

Or, see teacher behaviour as evidence of student thinking (Morris, 2006).

Using evidence of student thinking is commonly seen as an important, or even crucial aspect of teacher noticing (incl. Santagata, 2011; Van Es, 2011; Talanquer et al., 2015; Lam & Chan, 2020), which researchers have been studying from several perspectives. They have, for example, looked at the extent to which teachers consistently refer to evidence when making claims about student thinking (e.g. Talanquer et al., 2015; Barnhart & Van Es, 2015). Others have studied whether teachers refer to specific events or interactions as evidence to support their claims about student thinking (e.g. Van Es, 2011; Taylan, 2017). More recently, researchers have additionally argued the need for investigating what sources (or forms) of evidence teachers use (Lam & Chan, 2020).

Teacher noticing is often investigated in professional development or teacher education settings. In such settings, teachers tend to have some time to review a premade selection of potential evidence of student thinking (e.g. Talanquer et al., 2015; Barnhart & Van Es, 2015; Dalvi & Wendell, 2017). In real classroom situations, however, teachers get bombarded with potential, and often fleeting evidence of student thinking (B. Sherin & Star, 2011). Moreover, teachers are facing the pressure of having to make instant instructional decisions (Jacobs et al., 2011). Lam and Chan (2020) suggested that these characteristics of in-the-moment noticing emphasise the need for teachers to home in on sources of evidence which are more revealing of the content of student thinking. Students' nodding heads in response to a teacher question, for instance, are typically less revealing of student thinking than verbal or written replies (Hiebert et al., 2007). In studying preservice science teachers' noticing in response to video clips, Lam and Chan (2020) found that these teachers were not particularly sensitive to some of the more revealing sources of evidence that were available to them (e.g. students' verbal explanations and artefacts).

We are also interested in science teachers' use of sources of evidence in noticing student thinking, as this remains to be explored in design-based classrooms. Design contexts can offer teachers access to a particularly varied and perhaps unusual collection of potential sources of evidence, since physical artefacts like prototypes and design drawings play an important role in design processes.

4.2.3 Design planning and drawing as a noticing opportunity

For teachers to notice student thinking, this thinking needs to be observable (Luna et al., 2018). Our exploration of teachers' noticing during design-based science activities is set against the back-drop of design planning and drawing activities. Planning and drawing (elements of) potential design solutions are essential aspects of design processes, which we find embedded in many frameworks for design in (science) education (incl. Kolodner et al., 2003; Fortus et al., 2004; Crismond & Adams, 2012; National Research Council [NRC], 2012; English et al., 2017; Chusinkunawut et al., 2020). The learning-by-design approach, for instance, engages science students in a design planning phase in each design iteration during which student teams are prompted to generate and refine their ideas for a design solution, sketch and describe what they plan to construct, and justify design decisions based on experimental results (Kolodner et al., 2003). Such activities can stimulate students to share their thinking with others. For example, productive planning of design solutions in a team requires students to explain and justify design ideas to others for which they may make of use their thinking in various disciplines (English et al., 2017). Also, designs drawings have been described as providing teachers and students with a material basis for discussing design and science ideas (Roth, 1994).

Research suggests that evidence of students' thinking about science concepts may be found in a variety of sources during design planning and drawing activities. For instance, researchers have gained insight in student thinking by studying students' talk during interactions with other students and/or with teachers (e.g. Valtorta & Berland, 2015; Siverling et al., 2019; English et al., 2017; Guzey & Aranda, 2017). Researchers have also consulted students' design drawings, often in conjunction with annotations such as labels, descriptions and arrows (e.g. Fortus et al., 2004; English et al., 2017; Kelley & Sung, 2017). Fortus and colleagues (2004), for example, studied a team's drawing as well as written justification document of their design for an electrochemical cell which demonstrated that the students understood that the difference between the electrode's electrochemical potentials determined the cell's voltage. Whereas student drawings can be difficult to make sense of in themselves (e.g. what does that squiggly line stand for?), student writings or verbal explanations can help clarify what students mean (Neumann & Hopf, 2017). Researchers have also noted that students can express the meaning of design drawings by using gestures (English et al., 2017). For example, Roth (1994) found that a student indicated a force and its direction by animating a design drawing of a pulley system with a sweeping gesture.

In exploring teachers' in-the-moment noticing, we will zoom in on teachers' conversations with students while student teams are engaged in planning and drawing designs. Researchers have highlighted that whole-classroom conversations can provide opportunities for teachers to gain insight in and support students' thinking about science concepts during design projects (e.g. Roth, 1994; Kolodner et al., 2003). However, students typically spend a large part of a design project working within their team (e.g. more than half of a unit; Valtorta & Berland, 2015). Teacher-student conversations during small-group design activities may offer similar opportunities for teachers to notice student thinking. And, because teachers have the change to 'provide help as needed' as they travel from group to group (Kolodner et al., 2003), these may be important opportunities too.

4.2.4 Accessing and analysing teacher noticing

To study teacher noticing, which is situated in and integrally tied to instructional settings, researchers need to collect data in a contextualised way (Jacobs, 2017). Researchers have gained access to teachers' in-the-moment noticing by consulting video data on teachers' practice in conjunction with teachers' retrospective reports on their thinking in class (M. Sherin et al., 2011b; Nickerson et al., 2017). Teachers' actions can provide insight into their noticing, as teachers' noticing can influence their observable responses (Levin et al., 2009; Mason, 2011). But, only studying a teachers' practice may mean that instances are missed where teachers noticed something, and decided not to act on it (M. Sherin et al., 2011b). By asking for teachers' reflections on their practice, and showing teachers video clips of classroom situations to stimulate their recall, researchers can obtain such information and triangulate their data (Nickerson et al., 2017; Furtak, 2012). Although teachers have been asked to reflect on video clips of their practice in writing (e.g. Barnhart & Van Es, 2015), interviewing teachers can provide particularly rich data as researchers have the possibility to ask follow-up questions (Jacobs, 2017). Still, teacher noticing is notoriously difficult to study as its tacit, transient and situated nature poses various methodological challenges (e.g. Thomas, 2017; Chan et al., 2020). For instance, while retrospective interviews can present valuable insights, revisiting videos of classroom situations creates a new noticing opportunity for teachers outside of classroom constraints (M. Sherin et al., 2011b).

Chemical thinking framework

The use of frameworks describing student thinking in a certain content area helps researchers to determine what counts as evidence of a teacher noticing student thinking in that area (Nickerson et al., 2017). Rather than using a framework describing student thinking about a specific concept (e.g. Furtak, 2012), our study's open-ended design context and research interest called for a framework covering student thinking about a range of chemistry concepts. We found this in the chemical thinking framework (Sevian & Talanquer, 2014). The chemical thinking framework defines a set of crosscutting chemistry concepts which can be used to analyse students' ideas and reasoning in chemistry as they engage in authentic chemistry practices (Sevian & Talanquer, 2014). These six crosscutting chemistry concepts are chemical identity, structure-property relationships, chemical causality, chemical mechanism, chemical control and benefits-costs-risks. They relate to eleven 'progress variables' along which students' chemical thinking has been hypothesised to develop (Sevian & Talanquer, 2014; see Figure 4.1). Elements of this framework have been used to characterise student thinking in a variety of chemistry contexts (incl. Banks et al., 2015; Yan & Talanquer, 2015; Cullipher et al., 2015; Weinrich & Talanquer, 2015).

Using this framework allows us to capture the possibly wide scope of teachers' noticing of students' chemical thinking during the design activities, and to characterise this in terms of associated crosscutting chemistry concepts. But, while researchers have been identifying, for instance, students' underlying assumptions, conceptual modes, and modes of reasoning (Sevian & Talanquer, 2014; Yan & Talanquer, 2015), teachers' noticing of students' chemical thinking will likely manifest itself differently. Noticing student thinking in a science discipline has, for example, been found to take the form of teachers identifying a student's knowledge gap, (in)correct terminology, misconception, confusion or reasoning inconsistency (Coffey et al., 2011; Talanquer et al., 2015; Dini et al., 2020).

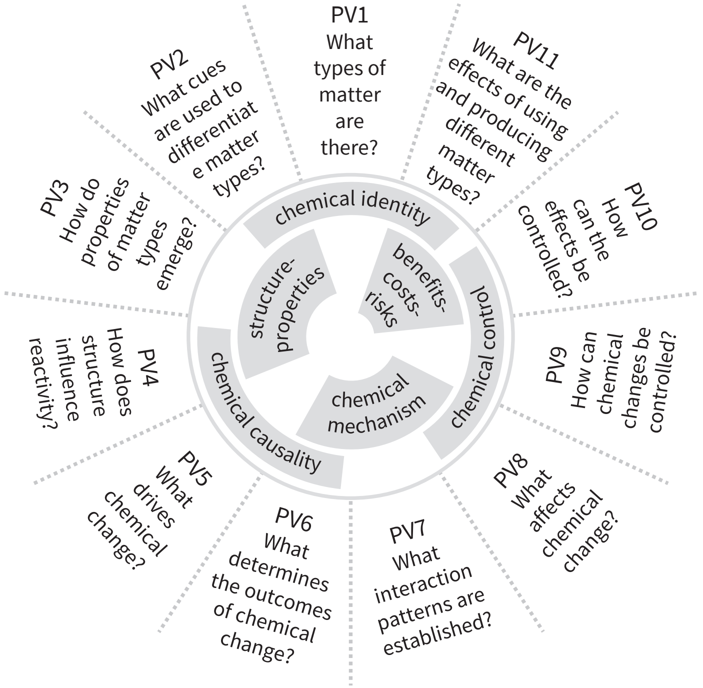


Figure 4.1. The crosscutting chemistry concepts and progress variables (PVs) of the chemical thinking framework (visually adapted from Sevian & Talanquer, 2014; with permission from the Royal Society of Chemistry).

4.2.5 Research questions

We formulated the following research questions to guide our explorative study, and gain insight into teachers' noticing in a design-based science classroom context:

RQ1. What chemical thinking do teachers notice during conversations with students who are engaged in design planning and drawing?

RQ2. What sources of evidence do teachers use in noticing students' chemical thinking during conversations with students who are engaged in design planning and drawing?

4.3 Methods

We used qualitative research methods to explore two chemistry teachers' noticing of students' chemical thinking, and use of sources of evidence during conversations with student teams engaged in design planning and drawing. We collected data on these teachers' noticing in the context of a design project for 10th-grade chemistry.

4.3.1 The design project

In the Dutch design project 'The thermo challenge', teams of 10th-grade chemistry students iteratively design a product that uses an exothermic or endothermic chemical reaction to change the temperature of a drink or food. The project was being developed by a professional learning community of secondary school chemistry teachers and researchers with the aim to stimulate students to apply and develop their understanding of chemistry concepts through engagement in design. The project specifically targets students' understanding of reaction energy, reaction heat and reaction rate. These concepts relate to progress variables 5, 8, 9, 10 and 11 of the chemical thinking framework (Sevian & Talanquer, 2014; see Figure 4.1). We present an overview of the design activities of each of the project's nine lessons in Appendix 1. The activities of lessons 3 and 7 centre on design planning and drawing. In addition to these activities, teachers also engage students in classroom rituals such as whiteboarding and relating a lesson's activities to a design cycle (as in, for example, Kolodner et al., 2003). Per lesson, one or two design canvasses were developed to support teams in the small-group design activities, and offer teachers potential evidence of student thinking. Canvasses contain prompts and empty spaces for students to respond to these prompts (e.g. 'sketch three different design ideas', lesson 3; 'How did you incorporate your understanding about reaction rate, colliding particles and activation energy in the design?', lesson 7). Teacher materials include presentation drafts, information on proposed classroom and lab activities, and examples of student work.

4.3.2 Participants

The two chemistry teachers participating in this study were voluntary members of a professional learning community on design in chemistry education and formative assessment. The PLC was facilitated by this study's researchers. Two of the six teachers of the PLC participated in this study. A year earlier, these teachers had implemented a previous version of the design project (with a smaller role for design drawing activities). These teachers were interested in participating. Ruben (pseudonym) had about 7 years of experience in teaching secondary school chemistry, and Vera (pseudonym) had about 3 years of experience. Both held a master's degree in (bio)chemistry, were qualified for teaching upper-secondary school chemistry, and had work experience as (bio)chemical engineers. The teachers were colleagues at the same urban school. During the PLC meetings leading up to this study, they had been engaged in analysing annotated design drawings collected in a pilot study, constructing content representations for the thermo challenge design project (CoRe; Loughran et al., 2004), discussing good practices for informal assessment conversations (referring to Ruiz-Primo, 2011), and formulating questions to help elicit students' understanding of chemistry concepts during the design planning and drawing activities (included in the teacher guide).

Each teacher selected one of their 10-grade chemistry classes for data collection. Teachers formed teams of about three students with the aim to promote learning. We asked teachers to choose two student teams to be the centre of our data collection, teams who would want to participate in the design activities and the research. Focussing on teachers' interactions with two design teams allowed for an in-depth analysis, while limiting close-up recording of students in class as this creates somewhat intrusive conditions. All students were informed about our overarching research aim (understanding how teachers can gain insight in student learning unobtrusively), and research process (incl. approach to data collection). Teachers and students gave us their consent. We will refer to the focus teams in the class of Ruben as teams A and B, and those in Vera's class as teams C and D. During lesson 3 only one of team B's students had been present.

4.3.3 Data collection

We collected two types of data to gain access to teachers' noticing: classroom and interview data. We collected classroom data during project lessons 3 and 7. These were the lessons in which students were planning and drawing designs in their teams, in preparation of constructing and testing prototypes the next lessons (see Appendix 1). Collecting data over two lessons rather than one meant that there were more opportunities for conversations between a teacher and focus team, potentially providing us with more revealing data. We conducted the retrospective interviews as soon as possible after each data collection lesson. These interviews required an additional research intervention between lessons 3 and 7.

Classroom data

We positioned a camera and an audio recorder (providing better audio quality) at each focus teams' tables. To obtain high quality video data (e.g. showing teacher and student expressions and gestures, and elements of teams' canvasses) we used cameras with a wide angle set to record in high resolution. An additional camera was positioned in the back of the classroom to capture what happened behind a team camera, and in the class as a whole. We aimed to limit the intrusiveness of the equipment itself by using small-size action cameras. The teacher had a personal audio recorder. We tested the whole setup during lesson 1 in each class, also as a way for the teachers and students to get acquainted with this approach to data collection. The first author and a research assistant were present during each lesson as equipment managers and to take field notes (in the back of the class, focus teams were positioned in the front).

Photos of design canvasses were taken at the end of each lesson as secondary data.

Interview data

We conducted a retrospective interview after each of these lessons, for which we prepared the collected video data by selecting conversations of interest. In selecting the video clips, we looked for conversations between a teacher and a focus team during the lesson's small-group activities (excluding interactions without student talk). Because of our focus on teachers' noticing of students' chemical thinking we also excluded conversations which concerned classroom logistics only (e.g. the time that was left; why a student of a team was absent; which design team would give which other team feedback). The selected conversations were cut from the lesson video, and separately recorded audio was added if necessary (the researcher also had a transcript available). We arranged the order of the clips in such a way that richer conversations (in terms of apparent instances of a teacher noticing students' chemical thinking) would be presented to the teacher first. The first and second author discussed the selection and order of clips before the interview took place.

In the retrospective interview, the researcher showed the teacher a clip and first asked broadly: Do you remember what you were thinking during this conversation? Can you tell me something about that? We then probed further for the teacher's noticing of student thinking, and use of evidence while revisiting the clip in parts (divided by a teacher's verbal responses). Our questions were: What did you infer here about student thinking? Why did you think students were thinking that? This approach was repeated for each clip. The semi-structured interview set up also allowed for asking follow-up questions (e.g. What do you mean by that? Did you realise that at the time, or is this standing out to you now?). We also asked teachers about their responses to students during the conversations, but those teacher interview comments are not the focus of this present study. At the end of each interview, the teacher was asked what had stood out to them in conversations with other teams in the class. All interviews were audio recorded and transcribed.

4.3.4 Data analysis

We qualitatively analysed the data to gain in-depth insight in each teacher's noticing of students' chemical thinking, and use of sources of evidence. We consulted videos and transcripts of the conversations between a teacher and focus teams in class in conjunction with transcripts of the retrospective interviews conducted after the design lesson. Throughout the iterative analysis procedures we relied on memo writing to document our analytic reflections (Saldaña, 2016), and table displays to compare and categorise the data (Miles et al., 2013). While we kept revisiting the video data, we also wrote detailed descriptions of video observations allowing us to zoom in on and record aspects of the videotaped conversations relevant to our research questions (Saldaña, 2016). We occasionally referred to secondary data sources, such as teams' design canvasses, to help us interpret the data. The first author did the bulk of the analyses, while the first and second author met up during the iterative processes to study video and interview data, and discuss observations, coded excerpts and emerging patterns until reaching consensus.

In addition to these general data analysis processes, we also employed the following specific procedures to answer our two research questions.

Analysing teachers' noticing of students' chemical thinking

We focussed our analysis on those conversations between teacher and student teams which had been selected when preparing the retrospective interviews (see the data collection for the selection criteria). Four conversations between Ruben and focus teams were retrospectively discussed by the teacher in the interviews (one per team per lesson; 60 to 90 s in duration). Two other conversations had not been discussed due to time constraints, and were not included in this analysis (team A, lesson 3; team B, lesson 7). In Vera's case, five conversations had been selected and retrospectively discussed (one per team per lesson, and a second conversation with team C in lesson 7; 25 to 80 s in duration).

We first studied the classroom and retrospective interview data for each conversation for indications of a teacher noticing student thinking. In the classroom data, we inferred a teacher's noticing by studying the teacher's verbal and non-verbal responses for influence of the teacher having noticed student thinking (Mason, 2011; Levin et al., 2009; Haug & Ødegaard, 2015). Such responses included a teacher rephrasing observed student thinking, and giving an explanation or suggesting a student activity that addressed a certain idea. For example, Ruben's responses to a student question concerning the reusability of ammonium chloride included giving a short verbal explanation 'no, because it reacted so it's become another substance', which was identified as an instance of the teacher noticing student thinking. We also examined a teacher's interview comments for references to student thinking, taking into account that this may appear in a variety of forms, such as a teacher describing a gap in a student's understanding, a failure to remember or an inconsistency in a student's reasoning (Talanquer et al., 2015; Dini et al., 2020). For instance, Ruben's statement 'so, then I thought, she apparently thinks that the substance does not get used up, or only got dirty or something' was identified as the teacher noticing student thinking (teacher describing an underlying assumption driving student thinking; Dini et al., 2020). Using the table displays, we constantly compared our analysis of the classroom and interview data to verify our interpretation of the data. During this process, we found instances where a teacher seemed to notice 'new' student thinking in the retrospective interview. These typically coincided with teacher statements like 'What I realise now [...]' and 'No, I don't think I noticed that before..'. As we were interested in teachers' noticing of student thinking in class, we excluded these instances.

We then sought to characterise each teacher's noticing of students' chemical thinking. To this end, we used the chemical thinking framework (Sevian & Talanquer, 2014) to identify whether instances of a teacher noticing student thinking, as identified in the previous analysis phase, involved students' chemical thinking. And, if so, to classify to which progress variable (see Figure 4.1) the teacher's noticing of chemical thinking related. During this coding process, we constantly compared our data (incl. student contributions) to the findings of previous studies in which researchers used elements of the chemical thinking framework to characterise student thinking (incl. Banks et al., 2015; Yan & Talanquer, 2015; Cullipher et al., 2015; Weinrich & Talanquer, 2015). For instance, Ruben's recognition that a student did not have knowledge about the melting points of plastics was identified as noticing chemical thinking, and coded as relating to progress variable 2 (melting points can be thought of as a cue to differentiate matter types; Ngai & Sevian, 2017). In the findings section, we provide thick descriptions of each teacher's noticing of students' chemical thinking per progress variable.

Analysing teachers' use of sources of evidence

We iteratively developed codes distinguishing sources of evidence which teachers used in noticing student thinking during the conversations, and we applied these codes to the classroom and interview data. We based our coding on sources of evidence as differentiated by others (incl. Cowie & Bell, 1999; Roth, 1994; Ruiz-Primo, 2011; Lam & Chan, 2020; Luna et al., 2018), and adapted and created new codes to account for what we observed in our study's data (Miles et al., 2013). Following our holistic perspective on teacher noticing, we included instances of teachers attending to evidence of student thinking, as well as teachers supporting their interpretations with evidence when coding the data (Superfine et al., 2017). In the video data, we inferred teachers' use of evidence from its influence on teachers' responses rather than examining, for instance, only the direction of teachers' gaze (Mason, 2011). For example, observing Ruben to use the same type of hand gestures as a student had just used when talking about the team's prototype and its materials, indicated that the teacher had paid attention to the student's gestures. We also examined teachers' interview comments for references to evidence of student thinking. For instance, Vera commenting (in response to the interview question 'And, why did you think he thought that?') with 'Because he says "do we need to know that precisely or not"…' indicated that the teacher used evidence from the source of student talk. In Table 4.1, we present the developed codes (incl. examples from data).

Table 4.1. Codes distinguishing sources of evidence used by teachers in noticing student thinking during conversations surrounding design planning and drawing activities.

Code	Description	Examples from data (interview comments; video observations)
Talk	Teacher using student talk as a source of evidence	'Because he says "do we need to know that precisely or not"…' (Vera, team C, lesson 7); Observing the teacher to listen and reply to a student asking a question (Vera, team D, lesson 3).
Design drawings	Teacher using students' (annotated) design drawings on design canvasses as a source of evidence	'[…] you look at the drawing and she hadn't drawn much' (Ruben, team B, lesson 3); Observing the teacher to lean over and look in the direction of a team's design drawing while a student points at and explains one of its elements and responding by smiling, nodding and saying 'fun' (Ruben, team A, lesson 3).
Notes and graphs	Teacher using students' notes or graphs on design canvasses (not a direct part of students' annotated design drawings) as a source of evidence	'[…] because she has experimental observations standing next to it with a smaller amount of substances, and there the temperature is lower' (Ruben, team B, lesson 3); Observing the teacher to read out loud a team's canvas notes (Vera, team D, lesson 7).
Prototypes and materials	Teacher using students' physical prototypes or construction materials as a source of evidence	'I didn't understand well why he was gonna stop with that bottle […] just that they were saying goodbye to that thing' (Ruben, team A, lesson 7); Observing the teacher to simultaneously look at, tap on and comment on a team's prototype (Ruben, team B, lesson 7).
Gestures	Teacher using student gestures as a source of evidence	'She's pointing to the canvas of the lab lesson' (Ruben, team B, lesson 7); Observing the teacher to use similar gestures as a student just used representing a prototype and its materials (Ruben, team A, lesson 7).
Practical actions	Teacher using students' practical actions as a source of evidence	'He was kind of playing with those cans' (Vera, team D, lesson 7); Observing the teacher to comment on a student who is determining the volume of a container by saying 'o, you are checking how much it holds' (Ruben, team A, lesson 7).
Eyes, faces, heads and posture	Teacher using students' (moving) eyes, faces, heads or posture as a source of evidence	'[…], and then you do see her smile a little' (Vera, team C, lesson 3); Observing the teacher to look in the direction of students' nodding heads when having given an explanation and asked 'Yes?', and then to continue talking about something else (Vera, team D, lesson 3).

We then focussed on what sources of evidence teachers used in noticing students' chemical thinking specifically. We compared our coding of each teacher's use of sources of evidence to our earlier analysis of the teacher's noticing of students' chemical thinking (as determined in the previous analysis phase). As others have noted, trying to establish direct links between teachers' use of evidence and noticing of student thinking was difficult (Superfine et al., 2017). For instance, a teacher could refer to a certain source of evidence after having made several claims about students' chemical thinking without specifying which of those claim(s) had been informed by evidence from that source. We thus decided to look for patterns in teachers' use of sources of evidence per and across conversations, rather than per instance of a teacher noticing chemical thinking. We looked for patterns including those based on frequency, similarity, differences and sequences (Saldaña, 2016), and were informed by prior research on teachers' use of evidence (incl. Lam & Chan, 2020; Barnhart & Van Es, 2015). As in the previous analyses, we constantly compared our observations in the classroom and interview data to verify our interpretations. In the findings section, we present our characterisation of each teacher's use of sources of evidence in noticing students' chemical thinking.

4.4 Findings

4.4.1 Teachers' noticing of students' chemical thinking

Both teachers noticed chemical thinking while in conversation with focus design teams during the design planning and drawing activities. Ruben noticed chemical thinking in all of the conversations we studied (one per team per lesson). Vera noticed chemical thinking in two of the five conversations (team D, lesson 3; team C, lesson 7). Ruben's noticing concerned progress variables 1, 2, 6, 7, 8, 9, 10 and 11 of the chemical thinking framework (see Figure 4.1 for the framework). Vera's noticing of chemical thinking involved progress variable 11. We present thick descriptions of each teacher's noticing of students' chemical thinking in the following paragraphs.

Ruben

PV1 – What types of matter are there? We found that multiple of Ruben's noticing instances related to progress variable 1. In a conversation with students of team A (lesson 7), Ruben recognised that a student 'knew which materials insulate heat and conduct heat' but 'did not use some words'. Halfway into a conversation, this student had used the words metal and plastic while asking Ruben: 'Is it smart to, kind of, have the outside one made of plastic, and the inside one of metal? So that you don't pass on heat quickly with your hand to the bottle, but that… the substance can pass it on to the metal.'. As a response, the teacher rephrased the student's statement referring to conducting and insulating materials rather than metal and plastic. In the same conversation, Ruben also noticed student thinking regarding diversity in a matter class. The teacher identified that students were considering plastic as their only option for insulating material, whereas styrofoam, for example, could also be potentially useful. Ruben: ‘They had been converging, […] it was time to diverge.’. Regarding another conversation with team A (lesson 3), Ruben commented in the interview that he had noticed something he had never before. He had found that a student thought that ‘the substance does not get used up, or only got dirty or something’. A student of the team asked the teacher whether ammonium chloride, which the team wanted to use for the design they had drawn, could be reused. After having stimulated the student to rephrase her question, the teacher replied that it could not as the substance had reacted and become another substance. The student’s thought was perhaps not so strange, Ruben said retrospectively, as people can also perform actions repeatedly without getting used up.

PV2 – What cues are used to differentiate matter types? The teacher’s noticing of student thinking also related to PV2, specifically to seeing matter’s response to certain conditions as differentiating cues. In a conversation with team A, Ruben identified that a student was distinguishing heat conducting and insulating materials (lesson 7; also see the description under PV1). And, that another student of team A was still confused about metal as a heat conductor after this had been discussed. Ruben: ‘He had talked about it, I had repeated it, and then she says “OK, conducting material, metal right?”. […] I was thinking, eeeh but that’s clear now right, why are you still doubting that?’. Ruben also noticed that a student of team B was thinking about the ‘heat resistance’ of materials, and did not know the melting points of plastics (lesson 3). The student of team B had asked the teacher whether she could use plastic for her design, considering that there would be very high temperatures involved. Ruben replied that she could as ‘most plastics can withstand a hundred degrees’. Retrospectively the teacher commented: ‘She thinks that the materials that they use won’t withstand those temperatures. That she will have a problem. I can tell her that, that’s not knowledge that she possesses, the melting points of plastics. […] That “hundred degrees” was a little bit vague, I wanted to reassure her that the materials she uses can handle those temperatures.’.

PV6 – What determines outcomes of chemical change? Ruben’s noticing of student thinking which related to this progress variable specifically concerned seeing amounts of reactants as determining the outcome of a reaction (outcome in terms of a temperature change, not chemical products). During a conversation with team A (lesson 7), the teacher approvingly recognised that these students were indeed considering this aspect in their design. In a conversation with a student of team B (lesson 3), however, Ruben identified that a student was not considering this, and he explained it to her. In the interview, Ruben commented:

> She had tried it out already, but apparently it didn’t stuck. Sometimes that seems so explicit, that they do an experiment […], and that you can sort of assume that they understand

> that you get a higher temperature with more of the substances, and a lower temperature with less of the substances. But, that is not at all so straightforward, that it retains as knowledge when they have done such an experiment. That you actually need to discuss it explicitly or do something with it. When designing, you do something with that knowledge.

PV7 – What interaction patterns are established? In the conversation initiated by a student of team A asking whether ammonium chloride could be reused (lesson 3; also see the description under PV1), Ruben also noticed thinking related to progress variable 7 (crosscutting concept mechanism). The teacher commented that the students of the team seemed to think that 'reactants were not really necessary to make new substances'. In the interview, Ruben expressed his surprise as students had learned the definition of chemical reactions, had done a lot of lab work with reactions, and had written and discussed many reaction equations. After having told the team that ammonium chloride had become another substance, the teacher additionally responded with saying: 'Then you would need to turn it back into ammonium chloride first, but that's complicated.'. In the moment of the conversation, the teacher retrospectively commented, he had decided to address it no further as 'students were mainly interested in the consequences for their design, not in the concept of reactions'.

PV8/9 – What affects chemical change and how can chemical change be controlled? In a conversation with students of team B (lesson 7), Ruben noticed student thinking related to progress variables 8 and 9. We take these together here, as they were very entangled in the data. A student of team B had asked, referring and pointing to a prompt on lesson 7's design canvas: 'Just it's, "How is your understanding about reaction rate"… What do we do with that?'. The teacher replied: 'Well, we know that reaction rate can be influenced by a higher temperature, by a higher concentration, by the type of substance, and by a few other things. And you could use that knowledge to.. improve your design.'. Ruben retrospectively commented to have noticed that the students of the team 'have the knowledge, but they can't really apply it'. As the conversation continued, the teacher also noticed that one of the students showed 'a good beginning of understanding' how to use the factors to increase the rate of their chosen reaction.

PV10 – How can the effects be controlled? Ruben's noticing of student thinking also related to progress variable 10 (controlling benefits, costs and risks of using and producing different matter types). The teacher noticed that students of team A (lesson 7) 'drew good conclusions' for optimising their product based on understanding of different types of materials, heat transfer, the volume of their drink and amounts of starting substances required to reach a certain temperature. Ruben's responses during the conversation included saying 'that's a good idea' when a student had verbally explained an element of their new design solution while drawing it in the air. In a conversation with a student of team B, concerning potentially melting plastic (lesson 3), Ruben noticed that the student 'had recognised herself that material properties play a role in the design'. However, the student did not realise that she could 'regulate the temperature herself', which Ruben explained to her. The teacher also said to have noticed that students of team A were 'considering the consequences' of what they had just learned about ammonium chloride, concerning its non-reusability, for their design. Towards the end of a conversation with team A (lesson 3), students explained their drawn design idea of using a tea filter containing ammonium chloride to change the temperature of the drink (while also ensuring that users would not ingest ammonium chloride, according to the students). Ruben retrospectively commented: 'I thought, they are doing well. They are thinking about how their design works. They are justifying decisions for materials and for filters and stuff. Keep up the good work!'. In the conversation, Ruben responded to the students' explanations by nodding, smiling and saying 'fun' and 'OK'.

PV11 – What are the effects of using and producing matter types? Ruben also noticed student thinking regarding progress variable 11. In a conversation with a student of team B (lesson 3), Ruben noticed that the student was having difficulties in choosing a reaction for the team's design. The teacher's retrospective comments included: 'She was doubting which substances to choose, and that doubt has a relation with the temperature that they… that they saw during the experiment.'. The teacher also recognised that the student was 'worrying about' the risks that materials could melt, and that the food in their designed product could become too hot. In a conversation with team A (lesson 7), Ruben noticed that a student was considering and calculating the amount of heat required to meet their design's requirements. The team had come up with a new design solution, which was not based on the tea-filter idea anymore. In the interview, the teacher commented: 'I remember thinking for a moment, oh that's a pity, they want to abandon an original idea for a standard solution. […] But, as they are calculating, they are doing a good job.'. During another conversation with team A (lesson 3), Ruben noticed that students wanted to make their product reusable. As reusing ammonium chloride was not an option anymore, the teacher told the team they could sell it in separate packages which was 'good for revenue'. Ruben later commented: 'I thought, instead of reuse being a problem, I see it as an opportunity.'.

Vera

PV11 – What are the effects of using and producing matter types? Related to effects of using matter, Vera identified that students of team C 'had forgotten what Q represented' (lesson 7). One of the students had asked her, referring to a prompt on the design canvas: 'Mam, what do you mean exactly with "required Q"? Because I don't know what to fill in.'. The teacher was not surprised at the student's forgetfulness as the topic had been addressed in a previous lesson, and the particular student had missed parts of some lessons. In the conversation, the teacher told the team's students what Q stood for ('the reaction heat that needs to be released or gets used'). When the student subsequently asked whether that had to be calculated precisely, Vera said to have noticed that ‘he thinks it needs to be precise’. She told the student that they could make an estimation based on what they already knew. Vera also noticed a confusion among the students of team D regarding selecting a reaction for the design (lesson 3). A student had asked the teacher whether they needed to choose from the ones proposed in the project or whether they could choose their own ‘material’. Vera retrospectively commented to have thought: ‘That he was in doubt about that. That he thought “maybe I can also just cool it with ice cubes” or something.’. Vera verbally responded in class with: ‘No, you need to, like make a choice between experiment one or experiment two. Euh, so reaction one and reaction two of the exothermic or endothermic reaction that you have chosen.’.

4.4.2 Teachers’ use of sources of evidence

In studying what sources of evidence each teacher used in noticing students’ chemical thinking, we found that student talk was both teachers’ main source of evidence. We additionally found that the other sources of evidence as distinguished in Table 4.1 could play a supporting role in Ruben’s noticing of chemical thinking. We did not find this pattern for Vera. We describe this characterisation in more detail in the following paragraphs.

Ruben

Student talk. Student talk was Ruben’s main source of evidence in noticing student’s chemical thinking during the conversations. The teacher’s noticing of student thinking as described in the previous findings section was largely based on what students said. Throughout the retrospective interviews, Ruben referred to student talk as providing evidence of chemical thinking. For instance, concerning a conversation with a student of team B (lesson 3) Ruben commented: ‘My attempts at uncovering what’s confronting her are suddenly verified by a clear quote. I thought, OK she’s indeed concerned about the heat resistance of materials.’. The quote Ruben referred to was the student asking ‘So, then you can use plastic, for instance?’. In the video data, we would often observe Ruben to listen to talking students without interrupting, and to respond to (some of) the content of students’ talk. For example, when a student of team A was asking a question (‘so, metal right?’; lesson 7), the teacher turned to face her, and nodded while replying ‘metal conducts heat well’. That student talk was Ruben’s main source of evidence was furthermore highlighted by finding that the teacher’s noticing of students’ chemical thinking concentrated on those students of focus teams who talked relatively extensively (two of the students of team A, and one of team B). The teacher also commented in interviews that it was difficult for him to grasp what those students were thinking who were not very talkative (e.g. a team B student who ‘always says “Yes, I understand”, and then gets nothing at test time’).

Other sources. While student talk was Ruben’s main source of evidence, we found this teacher to use multiple sources of evidence in noticing students' chemical thinking. For instance, in a conversation with a student of team B (lesson 3), Ruben's noticing had been informed by evidence from the sources of student talk and annotated design drawing. Ruben commented in the retrospective interview:

> That's a combination of what she says in the moment, what had happened in the previous lesson when they had also been talking about temperature. Then I'd also thought that she was concerned about that high temperature. You look at the drawing, and she hadn't drawn much. She clearly hadn't made a decision for a substance. That was apparently what was holding her back. You always try to relate the question they ask to where they are in the design process. That quickly provides you with a lot of information.

Our video observations of this conversation included observing Ruben to respond to the student's verbal questions, and to look in the direction of her design canvas. We saw that all sources of evidence as defined in Table 4.1 had played a role in Ruben's noticing in at least one of the studied conversations.

Ruben appeared to rely more heavily on evidence from non-talk sources when students were not very talkative. The teacher learned, for example, about a team B student's chemical thinking because the student was 'pointing' at a certain design canvas element when 'asking half a question' (gesture and talk; lesson 7). Using evidence from multiple sources also helped the teacher to weigh the trustworthiness of identified evidence on student thinking. For instance, the teacher commented retrospectively that a student of team B 'confirms with her mouth' (talk; lesson 7) that she knew how to increase the reaction rate. The student had shortly stated in the conversation: 'We are figuring it out'. On the other hand, the teacher commented, 'she demonstrates that she doesn't know what to do'. This was demonstrated, the teacher said, by the student first resting her head on her hands (posture), and then being engaged in drawing the team's design (practical action; design drawing) instead of discussing ideas for influencing the reaction rate with the teacher and other team mates (talk). In the video of the conversation, we observed Ruben to nod in response to the student's short statement, and then to look in her direction multiple times as the conversation with the team continued. This example also illustrates our finding that non-talk sources provided Ruben with evidence of student thinking, but that the teacher could not conclusively determine what students were thinking if he had little access to student talk.

Vera

Student talk. Student talk was also Vera's main source of evidence in noticing student's chemical thinking. The teacher's noticing of student thinking as described in the previous findings section was informed by what students had said. Vera's interview comments specifically referred to student questions as requiring the teacher's attention, and suggesting some sort of issue in students' thinking. For instance, regarding the conversation with team C (lesson 7) Vera retrospectively commented: 'I think I was busy collecting prototypes, so I was actually not expecting this kind of question anymore. But, they clearly didn't understand something'. The question Vera referred to was: 'Mam, what do you mean exactly with "required Q"? Because I don't know what to fill in.'. In the videos of the conversations, we observed the teacher to prompt a student to repeat a question, listen to talking students (while also repeatedly cutting students off by starting to talk herself), and to respond to (some of) the content of student talk. For example, when a student of team B started asking a question ('Do you need to, like, make one of those two choices bet-'; lesson 3), Vera came closer, gave an initial reply ('Yes, you need to make a choice'), and then gave a longer reply when the student had extended his question a bit further.

In analysing the data we found no interview references to other, non-talk sources of evidence for those conversations during which Vera noticed chemical thinking. With the exception of a general statement that a raised student hand indicated to Vera that a student had a question (team D, lesson 3).

4.5 Discussion

The purpose of this study was to explore teachers' noticing of student thinking in a design-based science classroom context. We qualitatively analysed two chemistry teachers' in-the-moment noticing of students' chemical thinking, and use of sources of evidence as the teachers engaged in conversations with 10th-grade chemistry students who were planning and drawing designs. Our exploratory study's findings add to the growing knowledge base on teacher noticing in science and engineering design education, and provide suggestions for analytical instruments and future research.

Our findings regarding research question 1 demonstrate that the teachers noticed chemical thinking during conversations with students who were planning and drawing designs in their teams. This outcome is encouraging as researchers have noted that open-ended design challenges can result in an increased variety of student ideas, which may make attending to student thinking more complicated for teachers (Watkins et al., 2018). Noticing student thinking as it unfolds in class could, however, enable teachers to adapt their instruction and actions based on that thinking in order to support student learning (Hammer et al., 2012; Cowie et al., 2018). Previous research suggested that students' science thinking could become observable during conversations between teachers and students surrounding students' design plans and drawings (e.g. Roth, 1994; Guzey & Aranda, 2017). This study's findings reveal that teachers may use such conversations, at a small-group level, to become aware of students' thinking about chemistry concepts.

This study's use of the chemical thinking framework (Sevian & Talanquer, 2014), also yielded the unique finding that a chemistry teacher may notice student thinking concerning a variety of progress variables and crosscutting chemistry concepts in a design-based classroom context. Even within single conversations we could find Ruben to notice student thinking related to various crosscutting chemistry concepts (e.g. chemical identity, chemical mechanism and benefits-costs-risks). Conversely, Vera's case illustrates that a teacher's noticing scope may be quite narrow in terms of involved crosscutting chemistry concepts. Vera's noticing instances centred on progress variable 11, which is associated with the crosscutting concepts of chemical identity and benefits-costs-risks. While design projects typically target certain science concepts, research has shown that design activities can give rise to student thinking about a greater variety of science concepts (Siverling et al., 2019). We also observed this phenomenon in our study's data, and across teachers' focus design teams. Ruben's noticing reflected the range of crosscutting chemistry concepts which appeared to be relevant in students' thinking to a greater extent than Vera's noticing. We also found more instances of Ruben noticing chemical thinking during conversations with the design teams than in Vera's case. While the focus teams' students were planning and drawing designs, Ruben thus had more opportunities than Vera to tailor his actions in support of the students' thinking about a variety of chemistry concepts.

Our findings regarding research question 2 show that a teacher may draw on evidence from multiple sources in noticing chemical thinking during conversations in the context of design activities (e.g. student talk and gestures; Ruben). This is a promising finding, as blending evidence from multiple observable student behaviours can allow teachers to draw more accurate inferences about student thinking (Griffin et al., 2010). The analysis of Vera's use of sources of evidence suggests that a teacher may, on the other hand, use a less extensive variety of sources of evidence when noticing chemical thinking (a similar observation can be found in Lam & Chan, 2020). The findings additionally demonstrate that both teachers in this study used student talk as an important source of evidence in noticing students' chemical thinking. Researchers have similarly been turning to verbal student data to gain in-depth insight in students' chemical thinking (e.g. Yan & Talanquer, 2015; Banks et al., 2015). And, this finding was to be expected as we had purposefully focussed our study's design on teachers' conversations with students. However, contrary to our own expectations and recommendations in literature (incl. Roth, 1994; English et al., 2017; Kelley & Sung, 2017), we found no indications of either teacher using what students of focus teams had drawn or annotated as evidence. We did see that Ruben used whether students had been drawing or were in the action of drawing as evidence. As researchers we observed that there had, however, been conversations where teams' emerging design drawings and annotations contained supporting and even supplementary evidence of chemical thinking. But, in the information buzzing and high-pressure environment of teacher-student conversations, students' chemical thinking had also been observable to teachers in other, perhaps more transparent and revealing sources of evidence.

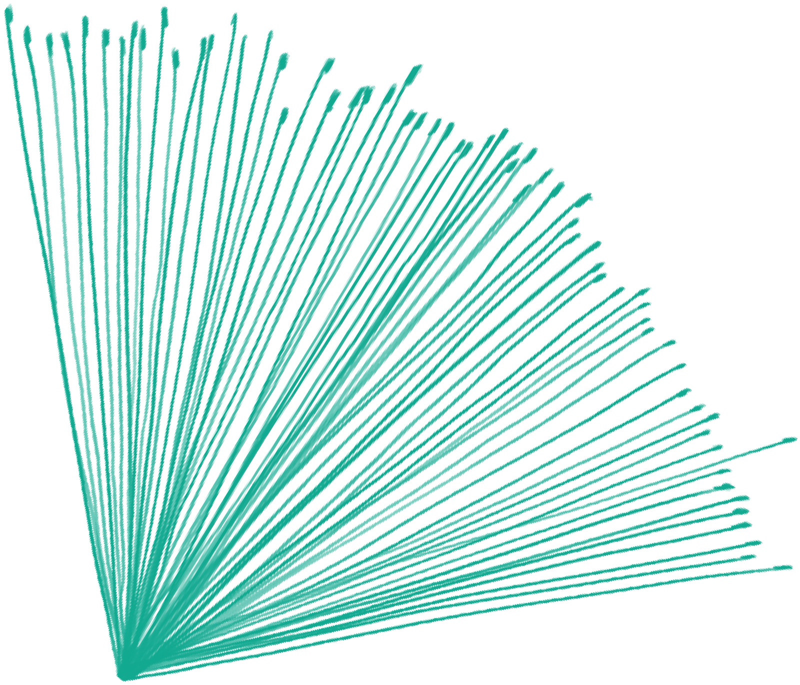
Teacher noticing appears to be influenced by multiple factors, like teachers' epistemological framing (Russ & Luna, 2013; Wendell et al., 2019), pedagogical content knowledge (Meschede et al., 2017), teaching experience (Erickson, 2011), and beliefs about teaching, learning and students (Van Es, 2011). Indeed, such factors may also have been at play in our study. For instance, Ruben had said to believe that teams' annotated design drawings 'contained no visible chemistry knowledge', which offers one possible explanation as to why we found no indications of the teacher using what student's had drawn or annotated as evidence. We also noted throughout the study that, while both teachers seemed to have multiple objects of interest during the conversations with designing students (as in Erickson, 2011), Ruben appeared to have a more substantial interest in students' (chemical) thinking. For example, Ruben stated in interviews that he valued that students were 'sharing their thinking' with him, and that he saw conversations with design teams as an opportunity to 'build bridges between chemistry and design'. Vera's interests during the conversations seemed to lie more with students' effort and task progress. And, with students' realisation that they were 'supposed to' design a product with separate containers for reactants, and a mechanism for bringing these together ('that's the critical point of the design which actually always goes wrong'). This could be another example of what we had found in an earlier study, namely that these teachers had a different focus in their goals for designing in chemistry education (Stammes et al., 2020).

A teacher's noticing in classroom contexts is additionally impacted by factors such as the extent to which students disclose their thinking, either voluntarily or prompted (Cowie & Bell, 1999). We observed, for example, that Ruben was asked more student questions, and a greater variety of questions in the course of the studied conversations than Vera. Moreover, how teachers respond in class based on their noticing shapes subsequent classroom events, and the new information which teachers can make sense of (M. Sherin et al., 2011a). Also, characterisations of teacher noticing like the one in this study are framed by the research conditions (e.g. influenced by the extent to which stimulated-recall interviews tapped into teachers' noticing; M. Sherin et al., 2011b).

4.5.1 Implications for future research

Teacher noticing is highly situated in nature, complicating the creation of teacher noticing measures that may be enacted across contexts (Thomas, 2017). Our study suggests, though, that the chemical thinking framework (Sevian & Talanquer, 2014) could offer one such measure for investigations into teachers' content-specific noticing in chemistry educational contexts. Characterisations of student thinking in a content area can support researchers in robustly identifying and describing instances of teacher noticing (Nickerson et al., 2017). Researchers' characterisations of students' chemical thinking based on elements of the framework proved to be useful for characterising teachers' noticing in our study's open-ended design context. In future work, researchers could also use descriptions of productive intermediate student understandings (Sevian & Talanquer, 2014), to evaluate and possibly stimulate the development of chemistry teachers' noticing. Learning to notice productive beginnings in students' thinking may help teachers to discriminate among a range of observable student ideas, and leverage those which have a high potential for supporting student learning (Stockero et al., 2017). Such studies could also explore the value of combining the chemical thinking framework with content-independent frameworks to characterise the nature and quality of teachers' developing noticing (e.g. Van Es & Sherin, 2008; Talanquer et al., 2015).

Our exploratory study points to more directions for future research. Researchers can use our codes distinguishing sources of evidence as a provisional analysis framework in other studies set in design-based science contexts. Follow-up studies could investigate teachers' use of sources of evidence among a bigger group of science teachers, and across different design activities. And, compare how teachers use various sources as they identify and perhaps connect different disciplinary aspects of students' thinking (e.g. design and chemical thinking). This may help us understand how teachers negotiate multiple foci of interest in design-based science classrooms. Such studies could also explore the benefits of asking teachers to point to elements of videoclips and student artefacts while talking about their noticing, and of videotaping teachers' interview responses as a way of gaining deeper insight in teachers' use of evidence. Future research efforts could additionally build on this study by exploring how science teachers can (learn to) use various sources of evidence in class, including design-based ones, to draw in-the-moment and high-quality inferences about students' thinking while students design.



5

Characterising students' conceptual understanding using design-authentic sources of information

5.1 Introduction

In the last decade, design-based science education has been finding its way into more and more science curricula and classrooms across the world (e.g. NGSS Lead States [NGSS], 2013; Board of Tests and Examinations [CvTE], 2014). While design can serve multiple purposes, it is frequently highlighted as a meaningful context for students to apply and develop understanding of science concepts (incl. Apedoe et al., 2008; Fortus et al., 2004; Kolodner et al., 2003; National Research Council [NRC], 2012). Trying to solve real-world design challenges offers students a purpose for using and developing understanding (J. S. Brown et al., 1989; Kolodner et al., 2003). Instrumental to implementing such a design-based pedagogy in schools, is knowing how to gain insight into students' understanding of science concepts as they design. Being able to characterise students' conceptual understanding in design contexts enables, for example, tailoring of instruction to students' learning needs (Black & Wiliam, 1998), and expansion of collective knowledge about design-based science teaching and learning (Carlson & Daehler, 2019).

To gain insight into students' understanding of science concepts in design contexts, research points to using design-authentic sources of information (e.g. students' design talk and annotated design drawings; Roth, 1994). Relying on sources of information arising from students' design activities (i.e. design-authentic) has advantages over the use of instruments archetypical of research and school cultures (e.g. interviews or content tests; also see J. S. Brown et al., 1989). For example, using design-authentic information allows evaluation of student understanding without disrupting the impact of the design context in which learning is embedded (e.g. Herrington et al., 2010). Consulting design-authentic sources of information may also provide deeper insight in the sophistication of students' understanding as compared to the use of more traditional assessments (e.g. Doppelt et al., 2008).

Reviewing existing literature does suggest, however, a need for exploring new ways to interpret design-authentic sources of information. For example, while point-based score systems allow relatively easy assessment of design artifacts (e.g. Fortus et al., 2004; Tas et al., 2019), we can learn more about students' understanding by paying close attention to what students mean rather than whether they are 'correct' (Coffey et al., 2011). And, while different analytic frameworks have been used for studying different types of data (e.g. one for students' annotated design drawings, another for written design evaluations, and a third for design talk; English et al., 2017), interpreting multiple source types using the same lens could support blending inferences into robust characterisations of student understanding (Griffin et al., 2010). We also see that studies utilizing design-based information have predominantly been conducted in elementary science and/or physics education (e.g. English et al., 2017; Kapon et al., 2020; Roth, 1994; Tas et al, 2019). How such sources may reveal conceptual understanding in other science subjects and school levels requires further investigation.

With this study, we aim to further unlock the potential of design-authentic sources of information for characterising student understanding of science concepts in design contexts. We will conduct an in-depth analysis of multiple design-authentic sources of information collected in a 10th-grade, design-based chemistry context. Design is also playing a more prominent role in secondary school chemistry curricula (e.g. CvTE, 2014; NGSS, 2013), but research in this area is still relatively scarce. In our analysis of the design-authentic information, we will focus on students' use of underlying assumptions about the nature of chemical entities and processes. Rather than assessing the correctness of understanding, for instance, the perspective of use of underlying assumptions takes into account the significance of students' everyday and implicit ideas, and their contextual sensitivity (Maeyer & Talanquer, 2013; Sevian et al., 2018; Sevian & Talanquer, 2014; Talanquer, 2009). While this perspective may therefore complement often-adopted ways to interpret design-authentic information, it has thus far been employed to characterise conceptual understanding based on more traditional types of information (e.g. interview and questionnaire responses). Whether a focus on use of underlying assumptions also facilitates interpretation of design-authentic sources of information, particularly ones arising from small-group design planning and drawing, will be explored in this study. We will explore this by combining and comparing what several sources of design-authentic information reveal of students' use of underlying assumptions in a design context.

As such, this study will increase our knowledge of how we can gain insight into students' conceptual understanding in design contexts through consulting design-authentic sources of information. As a by-product of the in-depth analysis process, our findings also provide a comprehensive characterisation of students' use of underlying assumptions in a secondary school design-based chemistry context.

5.2 Background

5.2.1 Design-authentic sources of information

When aiming to characterise student understanding, we tend to rely on information in the form of observable student behaviour, such as what students say, write, make or gesticulate (Griffin et al., 2010; Taber, 2013). For obtaining this information in design-based science education contexts, we can distinguish two main approaches (drawing on J. S. Brown et al., 1989). One approach relies on the implementation of instruments which are archetypical of school and educational research cultures. Cunningham and her colleagues (2020), for example, studied the impact of design-based units on students' understanding of science concepts using multiple-choice tests. Conducting interviews is another common method, particularly in research (e.g. Marulcu & Barnett, 2013; Schnittka & Bell, 2011). Design-based lesson materials available to science teachers have also been found to highlight this first way of collecting information (Peterman et al., 2017). We can contrast this approach with one where students' design activities are seen as giving rise to potential sources of information on students’ understanding of science concepts. English and King (2019), for instance, found evidence of students’ application of science concepts in students’ annotated design drawings. We define behavioural information arising from students’ design activities as ‘design-authentic’ (as in, for example, Peterman et al., 2017). Design-authentic sources of information which have provided certain insights into students’ understanding of science concepts also include students’ gestures, talk, and prototypes (e.g. English & King, 2019; Fortus et al., 2004; Valtorta & Berland, 2015).

Using design-authentic sources of information to gain insight in students’ understanding of science concepts has several advantages. For example, design-authentic sources of information tend to be readily observable in design-based classrooms (Kelly & Cunningham, 2019). When students want to make others grasp their design idea, for instance, they may be found to talk, draw, make notations and gesture (Roth, 1994). Using this kind of information means having the opportunity to characterise students’ conceptual understanding as they design. More conventional approaches, on the other hand, are often employed before and after a design-based unit (e.g. Cunningham et al., 2020; Schnittka & Bell, 2011). Such approaches may also undermine the impact of an authentic learning context, whereas authenticity can even give meaning to assessment (Herrington et al., 2010). Being embedded in an authentic context additionally offers students access to supporting and structuring cues, which can facilitate the use and continual development of conceptual understanding (J. S. Brown et al., 1989). Use of design-authentic information has resulted, for example, in researchers adjusting their conclusions on students’ understanding. For instance, Doppelt and colleagues (2008) remarked that classroom observations and design portfolios ‘showed that the ‘low achievers’ reached similar levels of understanding scientific concepts despite doing poorly on the pen-and-paper test’ (p. 34).

Because of their potential for providing insight into students’ understanding of science concepts in design contexts, we direct our attention to design-authentic sources of information in this study. Moreover, reviewing existing literature suggests that the field may benefit from exploring new ways for interpreting design-authentic sources of information.

5.2.2 Characterising conceptual understanding

Student understanding of science concepts can be characterised from a variety of perspectives, which we also see happening in research making use of design-authentic source of information. Researchers have, for example, examined students’ ability to relate science concepts to a design context (Valtorta & Berland, 2015). Others have used design-authentic information to characterise students’ understanding in terms of cognitive constructs, in particular misconceptions, alternative conceptions and scientific conceptions (e.g. Schnittka & Bell, 2011; Wieselmann et al., 2020). There are also cases where perspectives on student understanding remain somewhat elusive (e.g. Chusinkunawut et al., 2020), or appear to differ slightly from source to source (e.g. English et al., 2017). While research has shown that design-authentic information can indeed reveal aspects of students' understanding of science concepts, consulting the broader science education literature indicates that the field may benefit from incorporating additional views.

Research on cognition, for example, has highlighted the importance of students' implicit and intuitive understandings of their everyday world for science education (e.g. DiSessa, 1993; Vosniadou & Brewer, 1992). Characterising these ideas can, among other things, support identification of resources helping students progress towards more sophisticated understandings (D. E. Brown & Hammer, 2008). Some existing approaches for interpreting design-authentic information, however, rely heavily on students using scientific vocabulary, or even exclude data excerpts involving everyday understandings (e.g. Valtorta & Berland, 2015). Also, inferring misconceptions or alternative conceptions (as advocated in, e.g., Wieselmann et al., 2020) could inadvertently feed the common belief that teaching science entails fixing or preventing a list of common mistakes (Talanquer, 2006). Rather than evaluating student understanding against a 'body of correct knowledge', researchers have argued for interpretations reflecting how ideas are assessed in a discipline (Coffey et al., 2011). In design-based science contexts, assessment of ideas is based on, for example, the usability of ideas for solving a certain design problem (Kolodner et al., 2003). Some methods for interpreting design-authentic information, though, contrast with this view. For instance, Fortus and colleagues (2004) used scoring lists to evaluate whether students' use of science concepts as apparent in design artefacts was 'correct'.

These comparisons indicate that design-authentic sources of information may be studied from other perspectives still, possibly resulting in new insights into student understanding in design-based science contexts. In this study, we aim to explore affordances of one such approach in the context of design-based chemistry education. We therefore sought an analytic lens enabling characterisation of understanding of chemistry concepts in a design context. And, one with potential for studying several sources of design-authentic information. Integrating multiple forms of communication supports students in conveying what they mean (English et al., 2017; Roth, 1994), and blending inferences from multiple types of behavioural information aids robust characterisations of student understanding (Griffin et al., 2010). These requirements brought us to a perspective on student understanding which has received particular attention in recent chemistry education research: students' use of underlying assumptions about the nature of chemical entities and processes.

5.2.3 Use of underlying assumptions

Chemistry education researchers have found that many of the ideas students express when engaged in chemistry tasks, can be understood in terms of underlying assumptions about the nature of chemical entities and processes (Maeyer & Talanquer, 2013; Sevian

& Talanquer, 2014; Talanquer, 2006, 2009). Students may, for example, state that atoms or molecules expand when heated, or that atoms or molecules have the same density as the actual substance. Both these statements can be explained by students relying on the implicit assumption that the granules or particles that comprise a substance have the same properties as a macroscopic sample of the substance (Talanquer, 2009). Such underlying assumptions, like many cognitive resources, often operate unconsciously, and support as well as constrain reasoning in chemistry (Maeyer & Talanquer, 2013). Their activation depends on personal experiences and contextual cues, such as familiarity with and nature of a task (Weinrich & Talanquer, 2015). Investigations into students' and experts' use of underlying assumptions have also demonstrated differences in levels of sophistication of assumptions. While some assumptions are based on everyday experiences (like the example above), others involve more academic knowledge (Sevian et al., 2018; also referred to as having greater explanatory power; Weinrich & Talanquer, 2015). Expert chemists rely often on more normative assumptions, but may still make productive use of more everyday assumptions in certain situations. From the perspective of underlying assumptions, developing conceptual understanding can be taken to involve at least two main processes: an expansion of the range of assumptions available to a person, and an increasing awareness of these resources and the contexts in which they can be applied productively (Sevian et al., 2018).

Focussing on students' use of underlying assumptions may offer a complementing perspective for interpreting design-authentic sources of information. The perspective recognises the significance of students' everyday and implicit ideas, and the contextual nature of student understanding. Moreover, although not investigated in design-based chemistry classrooms yet, the importance of actively engaging students in real-world chemistry practices was a leading principle in the development of this perspective (Sevian & Talanquer, 2014). For example, the six crosscutting chemistry concepts and associated core questions guiding research into underlying assumptions were selected because of their importance in the work of chemical scientists and engineers (Figure 5.1; Sevian & Talanquer, 2014). Researchers have also suggested that studying the use of underlying assumptions may facilitate characterisation of conceptual understanding in design contexts. However, this has thus far been explored in one-on-one interview studies where students were asked design-related questions, rather than in the complexity of design-based chemistry classrooms (Cullipher et al., 2015; Sevian & Talanquer, 2014; Weinrich & Talanquer, 2015). Lastly, researchers have been able to characterise students' use of underlying assumptions based on student talk (e.g. Cullipher et al., 2015), and drawings combined with writings (e.g. Stains & Sevian, 2015). While these sources of information were not design-authentic, this observation suggests that studying students' use of underlying assumptions may offer a single analytic framework for interpreting multiple types of behavioural information.

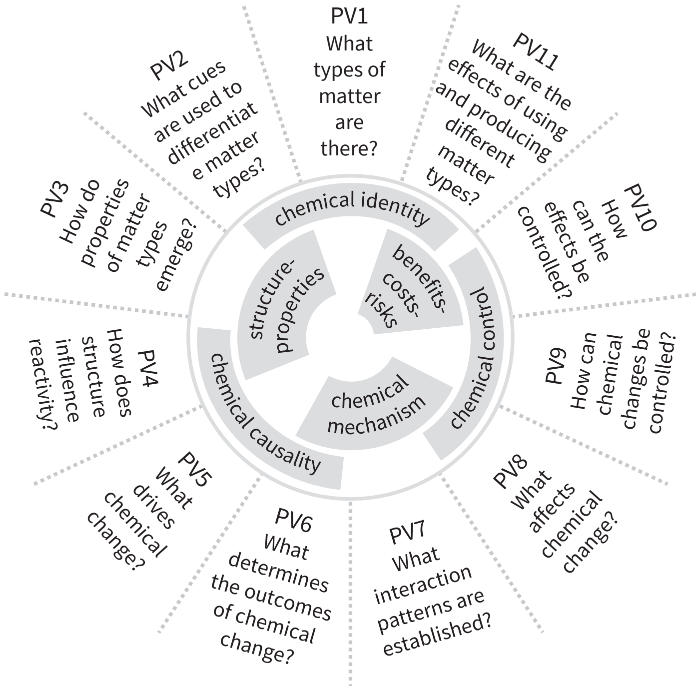


Figure 5.1. Crosscutting chemistry concepts and core questions (or progress variables, PVs) guiding research into use of underlying assumptions about the nature of chemical entities and processes. Reproduced and adapted from 'Rethinking Chemistry: a Learning Progression on Chemical Thinking' (Sevian & Talanquer, 2014) with permission from the Royal Society of Chemistry, and previously published in Stammes et al. (2021).

In this study, we explore affordances of this perspective for characterising students' conceptual understanding using design-authentic sources of information. Contrary to how this perspective is often applied, we will not limit our analysis to certain chemistry concepts. Researchers have noted that engaging primary school students in open-ended and multi-faceted design challenges can result in a particularly large variety of student ideas (Watkins et al., 2018). This can have important consequences for teaching. For example, while noticing student understanding in class can enable teachers to tailor their actions to students' learning needs (Cowie et al., 2018), this may be more complex when teachers are faced with a wide range of ideas (Watkins et al., 2018). We were interested in examining whether a focus on underlying assumptions would allow capturing some of the diversity of student ideas buzzing around in classrooms as chemistry students design. We will therefore include all six crosscutting chemistry concepts of the chemical thinking framework in our analysis, namely chemical identity, structure-property relationships, chemical causality, chemical mechanism and benefits-costs-risks (Figure 5.1; Sevian & Talanquer, 2014). Like others (e.g. Banks et al., 2015; Cullipher & Sevian, 2015), we will make use of the eleven, more detailed core questions to identify and characterise students' use of underlying assumptions concerning these crosscutting concepts. These core questions are often referred to as progress variables (PVs), as students' conceptual understanding has been hypothesised to develop along these lines (Sevian & Talanquer, 2014). For the purposes of this first study, we concentrate our efforts on exploring whether the perspective of underlying assumptions reveals a range of student ideas based on design-authentic sources of information. If so, this would open avenues for future work into, for example, development of students' use of assumptions in design contexts.

5.2.4 Talk and annotated design drawings

To be able to explore affordances of design-authentic sources of information, and a focus on students' use of underlying assumptions in a chemistry-design context, we will gather data as students plan and draw designs in small groups. These design activities play an important role in many frameworks for design-based science education (incl. Chusinkunawut et al., 2020; Fortus et al., 2004; Kolodner et al., 2003). Moreover, previous research, predominantly conducted in elementary and physics educational settings, indicates that students may make use of understanding of science concepts during small-group design planning and drawing (e.g. Chusinkunawut et al., 2020; English et al., 2017; Roth, 1994; Sung et al., 2019). For example, productively generating potential design solutions in a team requires students to explain and justify design ideas to each other for which they can draw on their conceptual understanding (English et al., 2017).

This study zooms in on three specific sources of information, which typically arise from design planning and drawing activities: students' talk within their design team, students' talk with the teacher participating in the team's conversation, and students' annotated design drawings. Students' use of underlying assumptions has been characterised using talk-, drawing- and writing-based information before (e.g. Cullipher et al., 2015; Stains & Sevian, 2015), making these design-authentic counterparts a good starting point for this study. Moreover, while researchers have hinted at the potential richness of students' talk and annotated design drawings, there are also indications that these sources may differ in what they reveal. For example, in design-thinking research students' talk has been described as more revealing of knowledge resources than students' design products (Guzey & Jung, 2020). Still, design drawings accompanied by annotations (e.g. labels, dimensions, narratives, arrows) have provided certain insights into students' conceptual understanding (English et al., 2017), and offer a source of information accessible once students have left the classroom. Also, on the one hand, formative assessment research tells us that teachers may leverage conversations with students to unobtrusively and purposefully elicit understanding (Ruiz-Primo, 2011), which can also occur in a design-based science classroom (Guzey & Aranda, 2017). On the other hand, teachers might only hear students' superficial retellings during such interactions, while students engaged in authentic tasks may be more effective in drawing out conceptions among each other (J. S. Brown et al., 1989).

Even though these examples suggest possible differences in what sources of information may reveal of students' conceptual understanding, this has not been thoroughly examined in design-based science education settings. Investigating this could, however, support those seeking insight into student understanding in design contexts. Including and distinguishing multiple design-authentic sources of information in this study, allows us to explore both what combining these sources reveals of students' understanding of chemistry concepts, as well as how these sources compare in what they reveal. While examining this, we will look at students' use of underlying assumptions at a small-group level. Student understanding can be studied at different space scales (e.g. Levin et al., 2018). The small-group level suits our explorative aim and research context (e.g. ideas inferred from an annotated design drawing may be group products).

5.2.5 Research questions

In this study, we aim to explore affordances of using design-authentic sources of information, and focussing on students' use of underlying assumptions about the nature of chemical entities and processes for characterising students' understanding of chemistry concepts in a design context. We will conduct this investigation in the setting of small-group design planning and drawing activities in a Dutch design project for 10th-grade chemistry education. Based on the review of literature presented above, we formulated two guiding research questions:

> RQ1. What do students' talk within their team, talk when the teacher participates in the conversation, and annotated design drawings combined reveal about the underlying assumptions which students use while planning and drawing designs?
>
> RQ2. How do students' talk within their team, talk when the teacher participates in the conversation, and annotated design drawings compare in terms of the variety of underlying assumptions they reveal?

5.3 Methods

We explored the two research questions in the context of a design project for Dutch, 10th-grade chemistry education (15-16 year olds). In the following sections, we describe this project, the participants, and approach to data collection and analysis.

5.3.1 Design-based chemistry project

In design project the 'Thermo Challenge', 10th-grade chemistry students iteratively design a product which harnesses energy from an exo- or endothermic chemical reaction to change the temperature of a self-chosen drink or food item. The project's aims include stimulating students to apply and develop understanding of chemistry concepts. Students' understanding of reaction energy, reaction heat and reaction rate is specifically targeted (relating to PVs 5, 8, 9, 10 and 11; Figure 5.1). Drawing design ideas and annotating drawings as a team is framed as a key design practice throughout the nine-lesson project. Drawing-related student activities include playing an introductory drawing game to get more familiar with drawing and to experience its relevance; formulating success criteria for design drawings with the class by discussing examples; and making annotated drawings as part of the 'instructable' of a teams' final design solution. The present study focusses on lessons 3 and 7 of the project, when students plan and draw designs in their design teams before constructing and testing prototypes in subsequent lessons. An overview of activities for each of the nine project lessons is provided as supplementary information (Appendix 1).

Design canvasses were developed to support students' activities, activate students' understanding of chemistry concepts, and offer potential sources of information for teachers (also see Puntambekar & Kolodner, 2005). Students use one or two new canvasses each lesson, and have access to their canvasses of previous lessons. Canvasses contain prompts and empty spaces for teams' responses (e.g. 'sketch three different design ideas', lesson 3; 'How did you incorporate your understanding about reaction rate, colliding particles and activation energy in the design?', lesson 7). They have a large, A3 paper size to support collaboration within a team. The main design canvas for lesson 3, which includes example drawings of potentially useful materials and objects, is provided as supplementary information (Appendix 2). During the design planning and drawing activities, students also have access to construction materials, and any prototypes already constructed. The teacher guide includes presentation drafts, information on proposed classroom and lab activities, examples of student work, and questions for eliciting student understanding in class drafted by teachers.

5.3.2 Participants

Two chemistry teachers and twelve 10th-grade students participated in this study. The teachers were voluntary members of a professional learning community on design-based chemistry education and formative assessment. They had implemented the Thermo Challenge design project a year before, and experience with other design-based chemistry projects. The teachers were selected because of these experiences, and their interest in participating. Ruben (pseudonym) had about seven years of experience in teaching secondary school chemistry, and Vera (pseudonym) three years. Both held a master's degree in (bio)chemistry, were qualified for teaching upper-secondary school chemistry, and had worked as (bio)chemical engineers. They taught chemistry in the same urban secondary school in the Netherlands, and had engaged the students participating in this study in design before.

Before the start of the Thermo Challenge design project, each teacher divided their 10th-grade chemistry class into teams of three students with the aim to promote learning. Teachers were asked to suggest two teams per class to form the centre of our data collection; teams of students who would want to participate in the design activities and our research. Focussing on two teams per class would allow an in-depth analysis of their design-authentic sources of information. Student teams A and B were in Ruben's class (a general secondary class), teams C and D in Vera's (a university preparatory one). Students and teachers were informed about our general research aim (understanding how teachers can gain insight into student learning), and research process (e.g. approach to data collection), and gave consent. Due to other obligations or illness, focus teams were not always complete. In lesson 3, two students of team B were absent, and one student of team C.

5.3.3 Data collection

We collected design-authentic sources of information in lessons 3 and 7 of the Thermo Challenge project, when students were engaged in small-group design planning and drawing. To gather students' talk arising from the design activities (both within a design team and when the teacher participated in the conversation), we used video and audio recorders. We positioned a small-size action camera with a wide angle (showing, e.g., who was talking), and an audio recorder (providing better audio quality) at each team's table. To gather students' annotated design drawings, we took photographs of their design canvasses after each lesson. The photographed drawings thus represent a source of information available when students have left the classroom. We collected secondary data by filming the class as a whole, recording teachers' talk, and taking field notes. We tested the video and audio setup in each class during the first lesson of the design project, also as a way for teachers and students to get acquainted with the approach to data collection.

5.3.4 Data analysis

We analysed the collected design-authentic sources of information in three phases. First, we prepared the data. Then, we examined the three design-authentic sources of information from the perspective of students' use of underlying assumptions, characterising which underlying assumptions students used during design planning and drawing (research question 1). Lastly, we compared the different sources of information in terms of the variety of assumptions they revealed (research question 2). Throughout the analyses, we discussed data and emerging codes among the researchers and with an external teacher-researcher, gaining new insights and settling on interpretations. In the following sections, we describe the three analysis phases in greater detail.

Preparing data

We transcribed students' and teachers' talk ad verbatim (in Dutch), and uploaded the transcripts and photographs of teams' design canvasses into nVivo. As we planned to examine what students' talk within their design team ('talk within team') revealed compared to students' talk while their teacher was participating ('talk with teacher'), we coded the transcripts for these two conditions. We consulted the video data to help us distinguish this. Regarding the design canvasses, which consisted of several spaces, we marked teams' design drawings and any annotations (e.g. labels, narratives, arrows; English et al., 2017) for subsequent analysis.

Characterising underlying assumptions

Next, we qualitatively analysed the transcripts of students' talk and photographed annotated design drawings in nVivo with the aim to characterise which underlying assumptions about chemical entities and processes students used while planning and drawing designs (research question 1).

To identify and code underlying assumptions in the data, we used the eleven progress variables (PVs; see Figure 5.1), and previous characterisations of underlying assumptions as a lens (incl. Banks et al., 2015; Cullipher et al. 2015; Ngai et al., 2014; Weinrich & Talanquer, 2015; Yan & Talanquer, 2015). For example, previous research has shown that students can use the assumption that matter belongs to distinct classes of stuff with different perceivable properties, usages or origins (PV1; Ngai et al., 2014; Ngai & Sevian, 2017). We also encountered this assumption while examining our data, such as when a student of team C said: 'if you just make the sides of that thing heavy, really like with iron or metal, you know, or with wooden blocks'. To this student, iron, metal and wooden blocks belonged to the class of heavy matter. Through constant comparison, however, we noticed that two assumptions could be distinguished regarding classes of matter. Students assigned properties and usages differently to matter categorised as belonging to a 'normal', daily life matter class (e.g. wood, iron and metal being heavy) than matter belonging to a 'chemistry' matter class (e.g. metals conducting heat). For instance, from the viewpoint of chemistry matter classes, students often assigned characteristics based on names and formulas (e.g. anything called a substance might react). We thus developed two codes: 'normal matter classes' (1a), and 'chemistry matter classes' (1b). So, while previous characterisations informed our analysis, new codes could emerge which were better grounded in this study's dataset (also see Miles et al., 2013). For each progress variable, we organised underlying assumptions according to their level of sophistication. These decisions were again based on previous characterisations, and involved judging whether assumptions were based more on everyday experiences or on school chemistry knowledge (following Sevian et al., 2018). For example, assuming that matter belongs to normal chemistry classes (1a) is based more on students' everyday experiences than assuming matter to belong to chemistry matter classes (1b).

In this analysis phase, we also used source-specific coding strategies. For interpreting students' talk and the annotations accompanying students' design drawings, we relied on generally-employed strategies for inferring implicit cognitive resources. We paid attention to, for instance, the entity or phenomenon that students were talking or writing about, the predicates they used, and the nature of students' claims (see, for detailed explanations, e.g. DiSessa, 1993; Slotta et al., 1995; Weinrich & Talanquer, 2015). For interpreting students' annotated design drawings, we additionally turned to work on analysing visual data (particularly Freeman & Mathison, 2009). We paid attention to a drawing's physical features (e.g. thick vs thin lines could indicate different types of matter), design features (e.g. product consisting of several compartments could suggest that students considered that different types of matter may react), and relationship to classroom activities (e.g. similar shape drawn by students as drawn among canvas examples or during whole-class session suggesting choice for a certain type of matter). As others have noted (incl. Chusinkunawut et al., 2020), we experienced difficulties in inferring conceptual understanding, in our case use of underlying assumptions, when annotations were scarce. For example, the arrows in the design drawing shown in Figure 5.2 appear to signify heat transfer, suggesting that students considered thermal effects of using matter (PV11). However, we could not identify a concrete assumption, because what these arrows meant to students was unclear as well as how students determined this effect (which is relevant to PV11; Cullipher et al., 2015; Sevian & Talanquer, 2014). Annotations in the form of labels and/or narratives, on the other hand, allowed us to stabilise inferences (also see Freeman & Mathison, 2009), or were informative in themselves.

Figure 5.2. Design drawing with arrows and patterned shapes (team B, lesson 7).

As well as critically examining each source, we continuously went back-and-forth between the different design-authentic sources of information to develop a code list that could be used across sources. On a few occasions, we also referred to secondary data (e.g. videotapes showing student gestures and facial expressions). Making use of this information helped us understand what inferences might reliably be drawn from students' talk and annotated design drawings.

We started this analysis phase with examining the design-authentic sources of teams A and B. Subsequently including team C's data resulted in refining previously identified assumptions, and adding two new assumptions to the code list. Finally adding team D's data resulted in no new codes. In the findings section, we describe the underlying assumptions used by students while planning and drawing designs as revealed through this analysis. A list of codes and descriptions is also provided as supplementary information (Appendix 3).

Comparing sources of information

Lastly, we focussed on comparing the three sources of design-authentic information in terms of the variety of underlying assumptions they revealed (research question 2). To enable analysis-at-a-glance (Miles et al., 2013), we mapped the assumptions characterised in the previous analysis phase on a circle (Figure 5.3). Assumptions were organised per progress variable and sophistication (codes placed farther away from the centre of the circle represent more sophisticated assumptions). Using this basic map, we created diagrams displaying which assumptions had been identified in which sources of information, both across teams and per team (see Figures 5.7, 5.8 and 5.10 in the Findings). Using these diagrams, we looked for patterns and anomalies describing the variety of assumptions revealed by the different design-authentic sources. We checked our interpretations against the coded data, analytic memo's and field notes (Miles et al., 2013). In the findings section, we present the diagrams, and describe our observations.

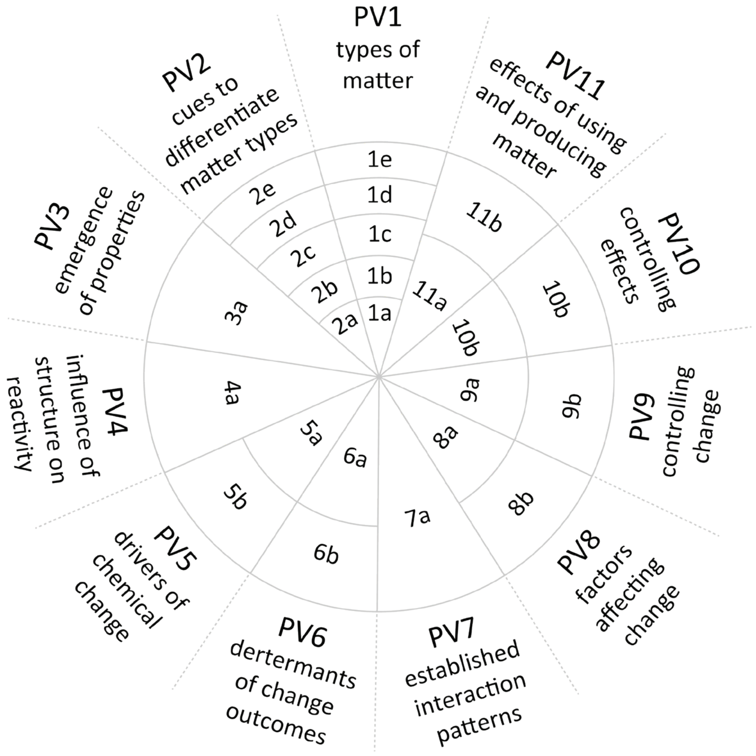


Figure 5.3. Map of identified underlying assumptions, organised per progress variable and level of sophistication. A description of each assumption code can be found in the findings section, and is available in tabular form in Appendix 3.

5.4 Findings

In the following sections, we present the analysis outcomes per research question. First, we describe what examining students' talk within their team, talk when the teacher participates in the conversation, and annotated design drawings from the perspective of underlying assumptions revealed about the underlying assumptions which students used while planning and drawing designs (research question 1). Second, we describe how the three design-authentic sources of information compared in terms of the variety of assumptions they revealed (research question 2).

5.4.1 Characterisation of underlying assumptions (RQ1)

Analysing students' talk within their team, talk when the teacher was participating in their conversation, and annotated design drawings from the perspective of use of underlying assumptions about the nature of chemical entities and processes led to the identification of twenty five underlying assumptions. Students of focus teams were (implicitly) drawing on these cognitive resources while planning and drawing designs during the Thermo Challenge design project. As the map in Figure 5.3 shows, at least one assumption was found for each of the eleven progress variables. These progress variables connect to six crosscutting chemistry concepts (see Figure 5.1). In the following sections we describe the assumptions identified per progress variable (PV), and illustrate these with examples from the data. A tabular overview is provided as supplementary information (Appendix 3).

What types of matter are there? (PV1)

We characterised five assumptions regarding types of matter (1a-e). Students were found using the assumption that matter belongs to one or more classes of 'normal', daily-life matter with certain characteristics (1a). Students of team C, for instance, first talked about needing cardboard or plastic cups for their squishy-cup design idea (i.e. cardboard and plastic cups belonging to the class of squishy matter). A moment later, the students discussed that they were probably not supposed to 'simply' use materials they would use at a fast-food place. Instead, they deemed it better to use 'special stuff', such as 'metals which can conduct coldness'. This second part of their discussion reflected students' use of assumption 1b, assuming that matter belongs to one or more classes of 'special' matter (also referred to as 'chemistry' matter) where labels suggest certain characteristics (e.g. the class of metals is known for its ability to conduct coldness). Students could see the same matter as a type of normal matter (1a) in one context, and as chemistry matter (1b) in another.

Besides classes of matter, students considered change and components of matter. Students used the assumption that (some) matter has a property that can be turned on or off, shared or used up while the matter's identity remains stable (1c). Guided by this assumption, team A had drawn their design idea (see Figure 5.4) of placing ammonium chloride in a filter that allowed water to pass through to induce the salt's cooling property. The filter would then retain the salt, and allow the cooled water to be drunk (according to the students). Students could also assume that the identity of matter could transform in certain conditions (1d), such as when a salt dissolves in water or when plastics melt at high temperature. And, students occasionally used the assumption that matter could be a mixture of multiple types of matter (1e; e.g. coffee consisting of water and coffee stuff).

What cues are used to differentiate matter types? (PV2)

Regarding cues used to differentiate and identify matter or matter types, we also distinguished five assumptions (2a-e). Students used the assumption that the way people use matter in daily-life situations was a cue (2a). For example, students of team C concluded that aluminium was an insulating matter type, because people feeling cold would get wrapped in aluminium blankets. Students also considered differentiating cues in what matter looks, feels or tastes

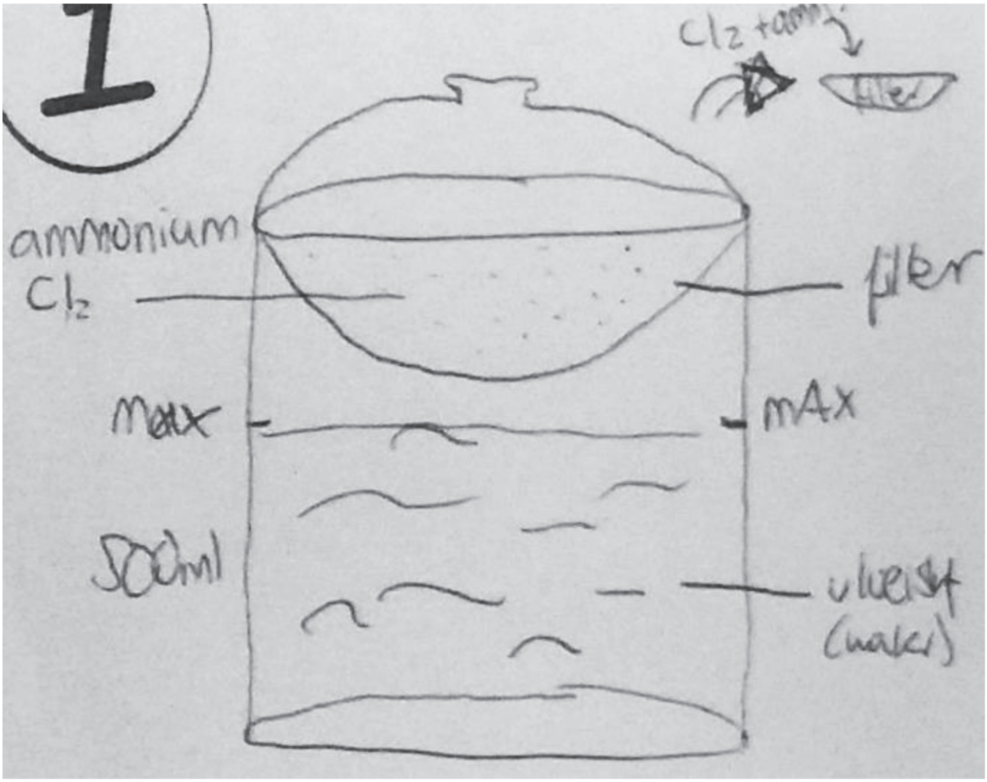
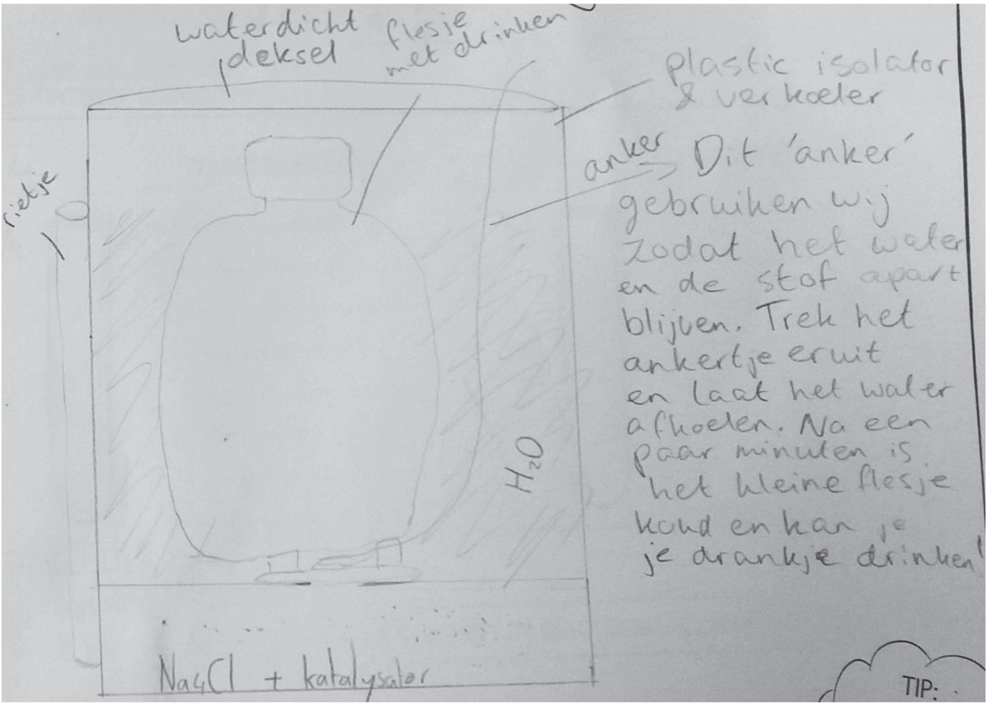


Figure 5.4. Annotated design drawing (team A, lesson 3).
The Dutch label ‘vloeistof’ reads ‘liquid’ in English.

like (2b), and in names and formulas used to describe matter in chemistry contexts (2c). For example, we found a student of team B relying on assumption 2b when asking her teacher whether magnesium powder was the same as magnesium ribbon. Use of assumption 2c can, for instance, be recognised in team C’s use of labels in their design drawing (Figure 5.5; e.g. ‘H_2O’ is different matter than ‘Na_4Cl’).

Greater attention to implicit properties of matter may be recognised in assumptions 2d and 2e. Students were found using the assumption that types of matter could be differentiated based on matter’s (expected) response to certain (experimental) conditions (2d). These conditions mainly involved changing temperatures (e.g. water is difficult to heat up; matter conducting heat well is a metal, not a plastic). Lastly, students could rely on the assumption that components of matter could be used to distinguish matter types (2e). For example, students of team D discussed that adding citric acid to water would result in a mixture of ‘citric acid in water’ which was different matter than water.



Dit 'anker' gebruiken wij zodat het water en de stof apart blijven. Trek het ankertje eruit en laat het water afkoelen. Na een paar minuten is het kleine flesje koud en kan je je drankje drinken!

Figure 5.5. Annotated design drawing (team C, lesson 7). The Dutch labels read: 'straw', 'watertight lid', 'small bottle with a drink', 'plastic insulator & cooler', 'anchor' and 'catalyst'. The narrative reads: 'We use this 'anchor' to keep the water and the substance apart. Pull out the small anchor and let the water cool down. After a few minutes the small bottle is cold and you can drink your drink!'.

How do properties of matter types emerge? (PV3)

Regarding emergence of properties, we found one assumption: that matter has the same properties at a macroscopic level as at the level of its constituting particles (3a). Students of team C talked about how freezing a drink meant that the drink's particles would also get frozen.

How does structure influence reactivity? (PV4)

For progress variable 4, we found that students could use the assumption that matter's grainsize influenced its reactivity (4a). This assumption was evident in a discussion among team C students, in which they decided to use finely grained ammonium chloride to improve the speed of their product's endothermic reaction.

What drives chemical change? (PV5)

We identified two assumptions regarding drivers of chemical change (5a-b). One was assuming that an external change agent, namely a person or a shift in surrounding temperature, drives change processes (5a). This assumption was evident in, for example, team C's written narrative accompanying their drawn design idea (see Figure 5.5). The narrative includes: 'We use this 'anchor' to keep the water and the substance apart. *Pull out the small anchor and let the water cool down*. […]' (italics added). Students also used the assumption that change is driven by a substance (5b). This could entail an active substance attacking a passive substance, or a substance acting as a facilitator of change between other substances. For example, a student of team A told her team mates that water induced the stuff (i.e. ammonium chloride) to start cooling. Assumptions 5a and 5b regularly appeared in the data as a sequence, where the first driver was an external change agent (5a) followed by a substance (5b).

What determines the outcomes of chemical change? (PV6)

The two assumptions identified for this progress variable (6a-b) predominantly involved considerations of outcomes in terms of temperature changes (rather than chemical products, for example). Students used the assumption that the duration of a change process determined its outcomes (6a). This was, for instance, evident in team A's discussion about utilising the option to stop their endothermic reaction once the desired temperature change was reached by separating starting substances. Students were also found to use the assumption that the amount (in grams or millilitres) of one or multiple of the starting substances determined a process' outcomes (6b). Students of team D, for example, discussed what amounts of starting substances they needed to get their drink to a higher temperature than during the first design iteration.

What interaction patterns are established? (PV7)

Regarding this progress variable, we found one assumption, namely that change processes proceed because substances are in contact (7a). For example, while in conversation with her teacher, a student of team A talked about different types of substances 'touching' during a reaction. And, a student of team D told his team that the contents of the reaction compartment had to be stirred continuously, rather than only at the start, to get the temperature to go down.

What affects chemical change? (PV8)

Assumptions regarding this progress variable (8a-b) often concerned reaction rate. Students used the assumption that rate is affected by the presence of substances (8a), specifically the presence of a catalyst, or concentration or (independent of volume) amount(s) of starting substance(s). For example, students of team D discussed that they had observed during a demonstration experiment, that the reaction speed had increased when a catalyst had been added. Students also relied on the assumption that the level of contact between different substances affected change processes and their rate (8b). For example, team A students talked about the need to shake their product so substances would mix better improving the reaction.

How can chemical changes be controlled? (PV9)

Assumptions concerning controlling change (9a-b) were in line with and often appeared together with those found for progress variable 8. Students used the assumption that reaction rates can be controlled, more specifically increased, by adding substances (new types of substances or greater concentrations or amounts of substances; 9a). For example, a student of team C told a team mate to 'write down that we'll add a catalyst to increase the reaction rate' (see the resulting label in Figure 5.5). Students were also found to assume that reactions and rates could be controlled by changing, specifically increasing, the level of contact between substances (9b). This assumption often involved students considering the need to shake or mix reaction mixtures, but was also apparent in students' considering finely graining a starting substance.

How can the effects be controlled? (PV10)

We came across a considerable diversity in students' ideas about ways to control the benefits, costs and risks of using (rather than producing) matter, and discerned two overarching assumptions. Students used the assumption that strategies for controlling effects can be thought of and decided on based on the perceived ease or enjoyment of designing or using products (products as designed in the project rather than chemical products; 10a). This could involve selectively accepting or dismissing effects, data, information, calculations or chemistry knowledge. For example, when students of team D had calculated the amounts of starting substances required to reach a certain temperature change, they thought their designed product would become too heavy to carry for its users, and started generating reasons for why their calculation was incorrect.

Students also used the assumption that identified positive and negative effects, data, information, calculations and/or chemistry knowledge can or need to inform ideas and decisions regarding controlling effects (10b). For instance, to efficiently harness the energetic benefits of their chosen reaction, students of team A used their understanding of insulating and conducting matter types. Their design drawing (Figure 5.6) shows two containers, one is labelled 'you put your water in here, [made] from metal', and another 'where reaction takes place, [made] from plastic'. This assumption could also take the form of students delaying making a decision to gather more information.

What are the effects of using and producing different matter types? (PV11)

We found that students considered a range of effects of using (rather than producing) matter. These effects mainly concerned (lack of) energetic benefits (often referred to as generating heat or coldness), health (e.g. risk of people consuming poisonous matter), safety (e.g. risk of people getting hurt by touching hot matter), and sustainability (e.g. striving to design reusable products). As for progress variable 10, we distinguished two overarching assumptions.

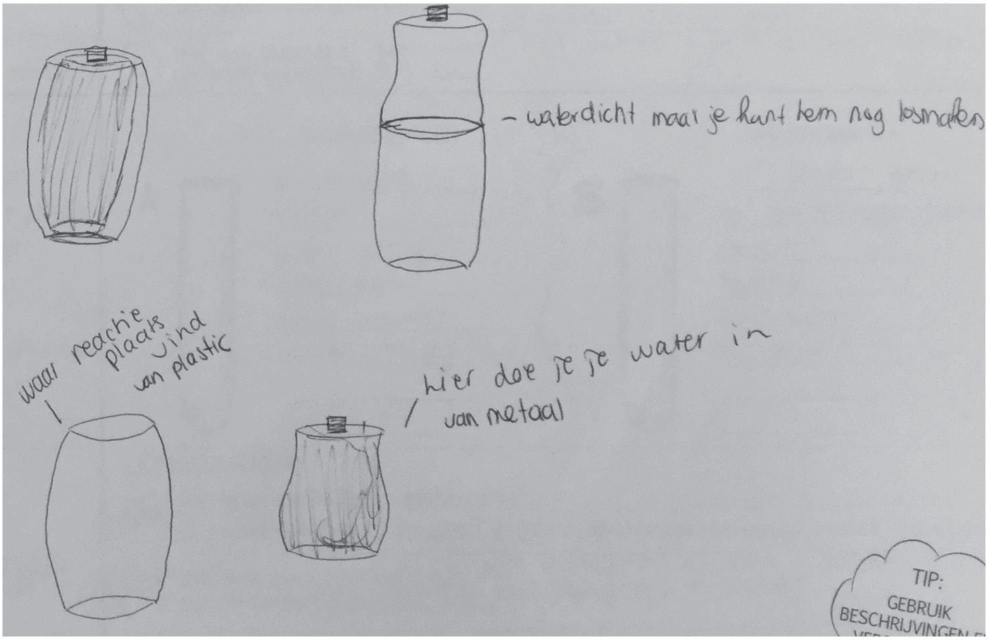


Figure 5.6. Annotated design drawing (team A, lesson 7). The Dutch labels read (from top to bottom and left to right): ‘watertight but you can still unfasten it’, ‘where reaction takes place, [made] from plastic’, ‘you put your water in here, [made] from metal’.

One was assuming that effects can be determined by taking a personal perspective or by taking the perspective of future users of designed products (11a). A student of team D, for example, told his team mates: ‘citric acid does not seem to me like something poisonous’. As for assumption 10a, this assumption could mean selectively accepting or dismissing data, information, calculations or chemistry knowledge. Students also used the assumption that determining effects required taking into account data, information, calculations and/or chemistry knowledge (11b). Guided by this assumption students of team D, for instance, discussed their experimental results looking for the ‘coldest’ and ‘quickest’ reaction to select for their design. Again, students could consider collecting more information to determine effects. Assumptions regarding progress variables 11 often appeared in the data together with those for progress variable 10.

5.4.2 Comparison of sources of information (RQ2)

In the following sections, we present diagrams displaying the variety of underlying assumptions as revealed by the different design-authentic sources of information, and describe our observations. First, we compare what each source of information revealed when looking across the four teams’ datasets. Next, we compare sources of information per team.

Across teams

When looking across teams, we see that all three types of design-authentic sources of information (i.e. students' talk within their team, talk when the teacher participated and annotated design drawings) could reveal use of underlying assumptions. The three diagrams in Figure 5.7 illustrate this, as all contain patterned fields (representing assumptions identified in at least on team's case). The left diagram in Figure 5.7 also shows that, when looking across teams, students' team talk revealed the greatest variety of assumptions. All twenty five assumptions could be identified in team talk. See Figure 5.3 for a map showing which fields in the diagrams correspond to which assumptions.

Comparing, across teams, which assumptions had been revealed by which sources of information shows that some assumptions were identified in only one source, some in two sources, and some in all three. Students' talk within teams had revealed assumptions not observed in the other two sources in any of the teams' cases. These were assumptions 2a, 3a, 4a, 8b and 9b. Assumptions apparent in two of the three sources were assumptions 1d, 1e, 2d, 2e, 6b and 7a (in students' team talk and talk with teacher), and assumptions 5a, 8a and 9a (in students' team talk and annotated design drawings). Assumptions identified across the three source types concerned types of matter (specifically 1a, 1b, 1c), cues for differentiating matter types (specifically 2b, 2c), drivers of chemical change (5a, 5b), controlling effects (10a, 10b), and effects of using matter (11a, 11b).

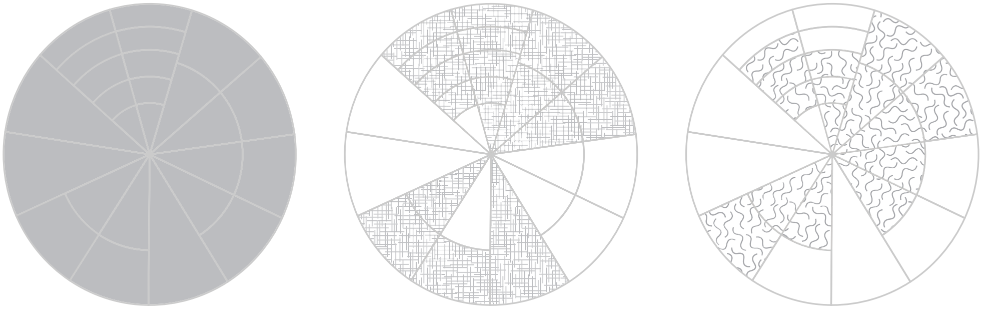


Figure 5.7. Diagrams showing across teams which underlying assumptions were identified in which sources of information. Grey (talk within team, left), striped (talk with teacher, middle) or scribbled (annotated design drawing, right) fields represent assumptions identified in a source in at least one team's case. White fields represent assumptions not identified in a source in any of the teams' cases.

Per team

When looking at our analysis of the three design-authentic sources of information per team, we see that each team's source revealed a unique set of assumptions. For example, in team A's talk with their teacher we could identify assumptions 1a, 1b, 1c, 1e, 2b, 2c, 2d, 2e, 5a, 5b, 6b, 7, 10a, 10b, 11a and 11b (Figure 5.8; top row, middle column). And, in team C's annotated design drawings we observed assumptions 1a, 1b, 1c, 2c, 2d, 5a, 5b, 6a, 8a, 9a, 10b and 11a (Figure 5.8; third row, right column). Also, none of the examined sources held evidence of all twenty five underlying assumptions (i.e. none of the diagrams in Figure 5.8 are fully patterned). There was, however, a source of information in which we could not satisfyingly identify a single assumption: team D's design drawings. Their design drawings did not have labels or narratives which we relied on for inferring students' use of underlying assumptions (see Figure 5.9).

The diagrams in Figure 5.8 additionally illustrate that the relative extent of variety in assumptions identified in a source differed between teams, and between sources of a team. For example, students' talk when the teacher participated in the conversation revealed a relatively greater diversity of assumptions in the cases of teams A and B (teacher Ruben) than teams C and D (teacher Vera). And, while the source revealing the greatest variety of assumptions for team A was their team talk, it was students' talk with their teacher in team B's case.

Combining which assumptions the three design-authentic sources of a team revealed, yields unique sets of assumptions for each team. The diagrams in Figure 5.10 indicate, for example, that only team C's students used assumptions 3a and 4a (involving emergence of properties and influence of structure of reactivity). And, that students of teams A and D used assumptions 1e and 2e (concerning components of matter), which was not observed in team B's and C's case. But, where students of team A used assumptions 8b and 9b (concerning chemical control), team D students used assumptions 8a and 9a.

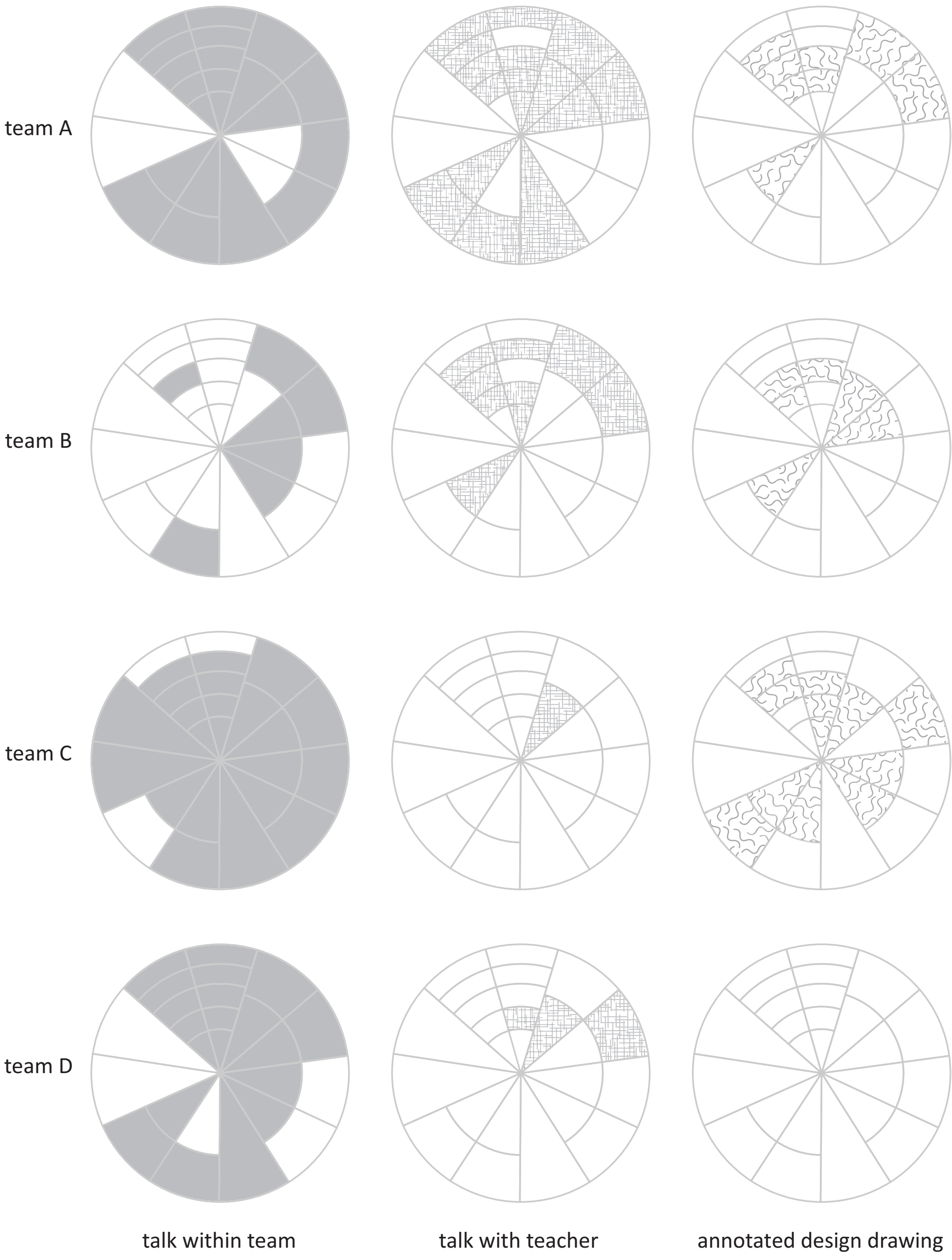


Figure 5.8. Diagrams showing per team which underlying assumptions were identified in which sources of information. Grey (talk within team, left), striped (talk with teacher, middle) or scribbled (annotated design drawing, right) fields represent assumptions identified in a source. White fields represent assumptions not identified in a source.

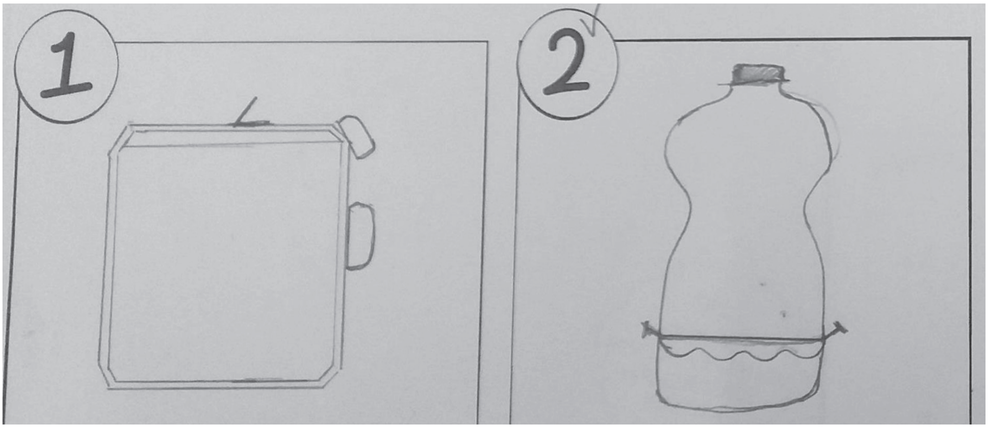


Figure 5.9. Design drawings without annotations (team D, lesson 3).

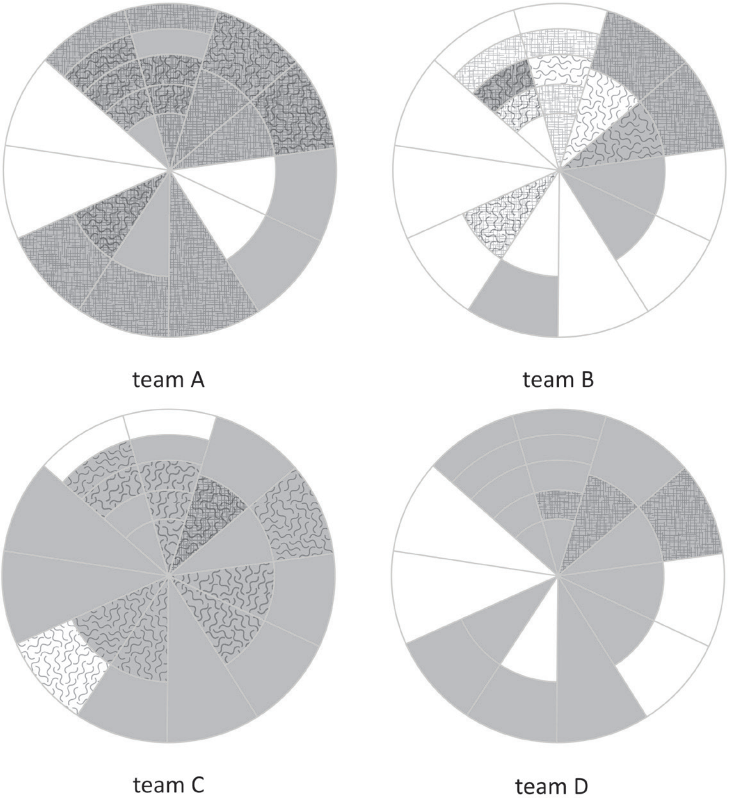


Figure 5.10. Diagrams showing per team the overlap of underlying assumptions identified in the different sources of information. Grey fields represent assumptions identified in the source ‘talk within team’. Striped fields represent assumptions identified in the source ‘talk with teacher’. Scribbled fields represent assumptions identified in the source ‘annotated design drawings’. White fields represent assumptions not identified in any source of that team.

Lastly, the diagrams in Figure 5.10 show differences between the four cases in terms of which source or combination of sources reveals the widest range of assumptions used among students of a team. Team A and D's cases present examples of a single source (namely team talk) revealing the greatest variety of assumptions. Other sources consulted for these teams reveal subsets of that variety. Team C's case, however, represents a situation where the greatest variety is revealed by combining inferences drawn from two sources (team talk and annotated design drawings). Use of assumption 5b was not observed in team C's team talk, but was apparent in their annotated design drawings. A third situation is represented by team B's case, where combining all three source types reveals the widest range of assumptions. In each source consulted for team B, assumptions were identified which we did not observe in the other two sources.

5.5 Conclusions and discussion

Curriculum reforms are stimulating secondary school science students to design as a way to meaningfully apply and develop understanding of science concepts (e.g. CvTE, 2014; NGSS, 2013). Instrumental to successfully implementing a design-based pedagogy, and expanding our knowledge of design-based learning and teaching, is understanding how we can gain insight into students' conceptual understanding as they design. Research suggests that students' design activities can give rise to sources of information (e.g. talk and annotated design drawings) from which one may infer understanding of science concepts (English et al., 2017; Roth, 1994). Using such design-authentic information also has advantages over more traditional ways to gathering information (e.g. content tests; J. S. Brown et al., 1989; Herrington et al., 2010). However, the potential of using design-authentic information for characterising conceptual understanding has thus far predominantly been explored in elementary and physics school settings. Moreover, we noticed opportunities for expanding our views on how design-authentic information may be interpreted. This included findings analytic perspectives suitable for interpreting different forms of design-authentic information. A promising lens for secondary school chemistry settings appeared to be students' use of underlying assumptions about the nature of chemical entities and processes (Maeyer & Talanquer, 2013; Talanquer, 2009; Sevian & Talanquer, 2014). But, before this study, this perspective had not yet been applied to design-authentic sources of information gathered in secondary school chemistry classrooms.

To address these matters, we set out to conduct an in-depth exploration of design-authentic information from the perspective of students' use of underlying assumptions. We examined three design-authentic sources of information collected in the context of 10th-grade chemistry students planning and drawing designs in small groups for a product harnessing chemical energy. We examined what students' talk within teams, talk with the teacher participating in the conversation, and annotated design drawings revealed of the underlying assumptions which students used while designing (research question 1). Moreover, we compared these three sources of information in terms of the variety of assumptions they revealed (research question 2). In the following sections, we draw conclusions and discuss findings per research question, consider limitations, and propose avenues for future research.

5.5.1 What the combination of design-authentic sources of information revealed (RQ1)

In-depth examination of the combination of design-authentic sources of information revealed twenty five underlying assumptions about the nature of chemical entities and processes used by students while planning and drawing designs. We found that these assumptions spanned all eleven progress variables and six crosscutting chemistry concepts defined by the chemical thinking framework (see Figures 5.3 and 5.1). Assumptions apparent in the design-authentic information could additionally be characterised based on their degree of sophistication (involving more everyday or academic ideas along a progress variable; see Figure 5.3).

Being able to capture the nature of underlying assumptions used by students when engaged in chemistry tasks, as we were in this study, means having a way to characterise students' conceptual sophistication in chemistry (Maeyer & Talanquer, 2013; Sevian & Talanquer, 2014; Talanquer, 2009). This study thus demonstrates that consulting design-authentic sources of information from the perspective of underlying assumptions can indeed facilitate characterisation of students' understanding of chemistry concepts in a design context.

Moreover, the findings regarding research question 1 suggest that the approach used in this study offers a valuable alternative to previously adopted ways to characterise conceptual understanding in design contexts. For example, using sources of information arising from students' design activities does not remove students from the physical and social environment framing students' use and development of understanding in design-based science classrooms. That is, however, typically the case when data is gathered through more traditional approaches like content tests and research interviews (as in, e.g., Cunningham et al., 2020; Schnittka & Bell, 2011; also see J. S. Brown et al., 1989). Also, this study's interpretation of design-authentic information from the perspective of underlying assumptions demonstrated that students in a class may consider a concept from multiple viewpoints when designing. We found, for instance, that students were making use of five assumptions considering their understanding of ways to differentiate matter types (incl. assuming daily-life use and components of matter to be differentiating cues). Characterising such a possible multiplicity of understandings is not facilitated by often-applied, but more narrow analytic perspectives on conceptual understanding (e.g. ones focussing on misconceptions or correctness of understanding; Fortus et al., 2004; Wieselmann et al., 2020). However, having access to approaches which can reveal a wealth of ideas in design contexts may support those aiming to promote students' awareness of heterogeneity in understanding of a concept, and their pragmatic use in different social contexts (e.g. Picón et al., 2020). Capturing the diversity in viewpoints among students can furthermore support teachers' noticing of and responding to student understanding in class (Cowie et al., 2018).

Another affordance of this study's approach to characterising understanding seems to lie in its suitability to reveal student understanding across chemistry concepts. As well as finding assumptions concerning concepts targeted by the design project (e.g. chemical control), we could identify that students used understanding of additional concepts while designing (e.g. chemical identity). Often, research into design-based science education zooms in on student understanding of one or a few science concepts (e.g. Apedoe et al., 2008; Fortus et al., 2004), as is also customary in research into underlying assumptions (e.g. Maeyer & Talanquer, 2013; Ngai et al., 2014). While this strategy has its uses, gathering design-authentic information and including multiple chemistry concepts when analysing this information allowed us to demonstrate that a range of chemical ideas can be activated in a design context. This study's approach thus offers opportunities for, for instance, evaluating students' ability to connect chemistry concepts as they design (rather than before and after students design as in Apedoe et al., 2021).

5.5.2 How the design-authentic sources compared in what they revealed (RQ2)

Comparing the three design-authentic sources of information (students' talk within their team, talk with the teacher participating, and annotated design drawings) showed that all three sources could reveal students' use of assumptions in the design context. The detailed comparison also demonstrated that the source revealing the greatest variety of assumptions differed between cases (Figure 5.8). We additionally found that use of an assumption was sometimes observable in only one of a team's three sources of information (Figure 5.10). Moreover, comparing the design-authentic sources of information of four student teams revealed a unique variety of assumptions for each team (Figure 5.10).

These findings stress the importance of consulting and combining multiple design-authentic sources of information when pursuing insight into students' conceptual understanding in a design context. This study thus reinforces, in a secondary school chemistry context, that paying attention to different forms of behavioural information can help grasp students' science ideas as they design (Roth, 1994). Our findings appear to be in contrast, however, with studies relying on one design-authentic source of information to characterise conceptual understanding (e.g. student talk; Valtorta & Berland, 2015), and studies advocating teachers to use a specific source (e.g. annotated design drawings; Kelley & Sung, 2017). Our study's in-depth comparison of multiple sources and cases was able to demonstrate that relying on one source of information may be a risky strategy as a selected source may reveal relatively little of the variety of students' understandings (e.g. when there is little talk within a team or little talk once a teacher joins in), or reveal no conceptual understanding (e.g. when a team's design drawing lack annotations to stabilise inferences). Recognising such possible limitations and benefits of using one or more design-authentic sources of information is not only relevant to research, but also to educational practice. For instance, beginning teachers frequently need to learn what type of information can provide insight into student understanding (Hiebert et al., 2007; Lam & Chan, 2020). This may also be the case for in-service science teachers implementing design-based approaches to learning (Stammes et al., 2021). Afterall, a design-based pedagogy is relatively new in science education, and so may be using design-authentic sources of information. This study's findings may aid efforts aiming to support (beginning) teachers in this.

The findings regarding research question 2 additionally show that the use of different lenses for studying different sources of information (as in, for example, English et al., 2017) can be overcome if desired. A focus on students' use of underlying assumptions about the nature of chemical entities and processes allowed us to make sense of all three sources consulted, and facilitated blending of our observations from these different sources. Being able to merge multiple types of behavioural information into coherent evidence sets can support robust characterisation of student understanding (Griffin et al., 2010). Also, our comparison of the four cases suggests that this study's approach to characterising student understanding has the power to differentiate between design teams based on the chemistry ideas students use while designing.

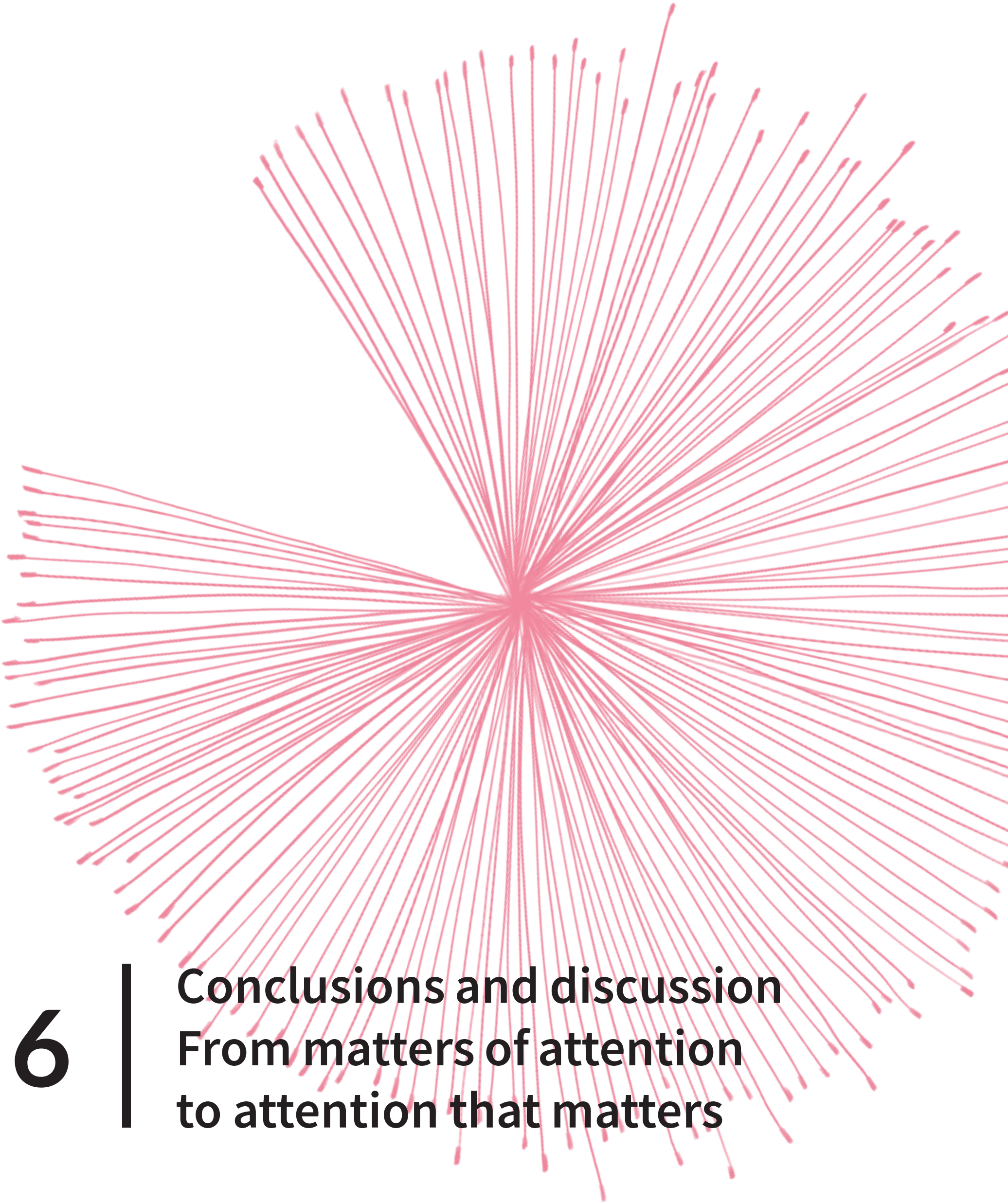
5.5.3 Limitations and avenues for future research

The small-scale setup of this study allowed an in-depth investigation into affordances of using design-authentic sources of information, and focussing on underlying assumptions for characterising students' conceptual understanding in a design context. While fitting our aim, this research design does entail that one should interpret our findings within the limits of the study's context rather than generalise findings. Also, while we took care to enhance the trustworthiness of findings when collecting and analysing data (e.g. by building on previous research and collaboratively examining data), another mind may yet bring another interpretation. Nevertheless, we see the characterisation of students' use of assumptions, and comparison of sources presented here as providing important insights into the possibilities of using design-authentic information. Moreover, this explorative study points to directions for future research.

Future research could examine what and how other, additional sources of design-authentic information may reveal of students' conceptual understanding as they design. Sources of interest include students' gestures and prototypes, but one can also envision research where teams' annotated design drawings are treated as a process-based source of information (e.g. by analysing video recordings of emerging annotated design drawings).

While the interpretation of such sources may also be aided by a focus on implicit use of cognitive resources like underlying assumptions, researchers could additionally explore what insights other perspectives on student understanding may yield. They could, for example, study interactions between implicit and conscious ideas (e.g. D. E. Brown, 2018), or the value of students' social connections (e.g. Wilson-Lopez et al., 2018). To benefit educational practice, in-depth theoretical research should be complemented with investigations into teachers' and students' (developing) use of design-authentic information. This type of research is emerging in elementary school contexts in particular (e.g. Watkins et al., 2018; Wendell et al., 2019), and we conducted a first exploration into chemistry teachers' use of design-authentic information (Stammes et al., 2021). However, more work is required to be able to fruitfully support implementation of design-based science pedagogies at the secondary school level.

Students' use of assumptions about the nature of chemical entities and processes in design contexts can also be investigated further informed by the work presented here. For example, we may expand our collective understanding of students' use of assumptions in design by transferring this study's approach to other chemistry-design contexts, and comparing findings (e.g. involving chemical synthesis or analysis; Sevian & Talanquer, 2014). Students' use of underlying assumptions while designing can furthermore be studied at more space and time scales (also see Levin et al., 2018). For example, students' individual use of assumptions is a topic requiring further investigation, as is the pragmatic value of students' chemical ideas in design contexts (e.g. Kolodner et al., 2003; Sevian et al., 2018). Researchers could also examine the evolution of students' use of assumptions during a design project. These types of research into students' use of underlying assumptions as evident in design-authentic sources of information could even support formulating a design-based chemistry response to the long-standing call to evaluate student understanding in ways reflecting assessment practices in a discipline (Coffey et al., 2011).



6

Conclusions and discussion

From matters of attention to attention that matters

6.1 Introduction

This thesis investigated *what* insight in student learning chemistry teachers can gain in the complexity of design-based chemistry education, and *how* in order to contribute to the field's budding understanding of teacher attention in science education settings, and support efforts seeking to foster teachers' expertise in design-based chemistry education. Gaining insight in student learning in the course of instruction means that teachers have the opportunity to tailor their actions to students' learning needs, and enhance student learning during a learning process (e.g. Black & Wiliam, 2009; Cowie et al., 2018; Hammer et al., 2012). Teachers' attention to student learning has therefore been gaining interest as an important facet of science teachers' expertise. But, despite its context-sensitivity (Russ & Luna, 2013), attention to student learning was not yet investigated in design-based chemistry contexts. This is a pressing matter, however, as chemistry curricular reforms are placing more emphasis on design (incl. Board of Tests and Examinations [CvTE], 2014; National Research Council [NRC], 2012). Moreover, attending to student learning has been described as particularly important, yet complex in design-based classrooms (Watkins et al., 2018).

Through conducting four qualitative, in-depth studies we explored different matters of attention in design-based chemistry education. Chemistry teachers' pedagogical ideas about design-based chemistry education were investigated (Chapter 2), as well as a teacher's multidimensional and dynamic attention to student learning in a design-based chemistry context (Chapter 3). Teachers' attention to students' chemical thinking, and use of sources of evidence was also investigated amidst the heat of a design-based classroom (Chapter 4). A detailed investigation of the affordances of using design-authentic sources of information for characterising students' understanding of chemistry concepts in a design setting was also conducted (Chapter 5). In the following sections, we summarise the findings and conclusions of these four studies. This is followed by a general discussion, and a description of limitations and avenues for future research. Practical implications for teachers and teacher educators are also presented. As such, this final thesis chapter addresses what attention could matter in educational research and practice regarding design-based chemistry education.

6.2 Findings and conclusions per study

In the study presented in *Chapter 2*, we examined chemistry teachers' ideas about teaching and learning in design-based chemistry education. The study was guided by the research question: *What pedagogical ideas do chemistry teachers have about design-based chemistry education?* We investigated teachers' pedagogical ideas in the context of a newly-initiated professional learning community on design-based chemistry education. To elicit the ideas of the community's six teachers, we conducted semi-structured interviews and asked teachers to keep a logbook during their implementation of a design-based chemistry project ('Expedition Toothpaste'). Questions and prompts were based on the four pedagogical elements of goals and objectives, student learning, instructional strategies and assessment (e.g. Magnusson et al., 1999; Van Gelder et al., 1973). Data analysis revealed that the teachers did not see learning to design (in chemistry) as an important goal of chemistry education, contrary to what one would expect based on design's central role in the chemistry discipline (Talanquer, 2013), and Dutch science curriculum (CvTE, 2014). Teachers said to teach design as a generally-applicable process or problem-solving approach. Teachers valued design more as a way to engage students in applying chemistry concepts, developing 'soft skills' (e.g. working independently, creativity), and applying or developing research practices. Teachers thought that design offered possible benefits for student learning such as the retrieval of conceptual understanding, increased motivation, and preparation for future school projects, studies and professional careers. However, bringing design into chemistry classrooms also posed challenges for teachers, including the selection of design situations that would engage students in making 'something concrete', and in applying chemistry concepts. While the community's teachers thus had multiple pedagogical ideas in common, ideas also varied per teacher. The findings show that chemistry teachers, like researchers (e.g. Fortus et al., 2005; Kolodner et al., 2003), can recognise design as a potentially rich learning context for students. However, whereas design has been described as a 'natural fit' for science education (see Roehrig et al., 2012), our findings suggest that the chemistry-specific nature of design is not necessarily naturally evident to chemistry teachers.

Chapter 3 presented a study where we sought to gain insight in the nature of teacher attention to student learning in design-based chemistry education, and in ways for capturing this attention. We conducted an in-depth investigation to characterise the multidimensionality of teacher attention in this context, as well as its possible dynamicity. This study's guiding question was: *What aspects of student learning form the focus of a teacher's attention in a design-based chemistry context, and how does this attention change over the course of a design project and reflection conversations?* To elicit teacher attention, we engaged one of the professional learning community's experienced chemistry teachers in weekly reflection conversations using a 'midstream modulation' approach (Fisher, 2007; Fisher et al., 2006) as she implemented a design-based chemistry project ('The Thermo Challenge'). We also leveraged the formative assessment focus of the community to elicit and examine her attention. Analysis demonstrated that the teacher attended to disciplinary aspects of student learning (i.e. students' chemical thinking, design practices and research practices), as well as more generally-relevant aspects of learning (i.e. students' social interactions, ownership, behaviour and emotions). Analysis at a finer grain size also allowed characterisation of what she attended to within these aspects of student learning, and revealed changes in her attention over time. The teacher's attention to students' chemical thinking and design practices became more focussed. Her attention to students' behaviour and emotions fluctuated, between negative and positive undertones. Attention to students' research practices, social interactions and ownership was, on the other hand, more consistent through time. These findings provide a first and comprehensive characterisation of a teacher's multidimensional and dynamic attention to student learning in a design-based chemistry context. Considering the value of 'reflection on practice' for enhancing teachers' expertise (c.f. Schön, 1983; Van Es & M. Sherin, 2008), these results also invite subsequent research into this study's adaptation of midstream modulation as a way to support development of teaching expertise.

Examining teachers' attention to student learning amidst the heat of a design-based chemistry classroom was the goal of the study presented in *Chapter 4*. The central question in this study was: *What chemical thinking do chemistry teachers notice in conversations with student teams during design planning and drawing, and what sources of evidence do they use?* By drawing on the construct of teacher noticing (M. Sherin et al., 2011a), we explored whether and what chemical thinking two chemistry teachers noticed during conversations with student teams engaged in design planning and drawing. As an important, even crucial facet of teacher noticing (e.g. Barnhart & van Es, 2015; Lam & Chan, 2020), we also studied teachers' evidence use. We collected both classroom and retrospective-interview data to access teachers' in-the-moment noticing, and used the chemical thinking framework for analysis (Sevian & Talanquer, 2014). This approach revealed that both teachers noticed chemical thinking during conversations with students. However, one of the teachers had more noticing instances, and noticed student thinking concerning a wider range of chemistry concepts (incl. chemical identity, chemical mechanism, chemical control and benefits-costs-risks), than the other. While students were planning and drawing designs, this teacher thus had more and more varied opportunities to support students' chemical thinking. Analysis of the teachers' evidence use showed that students' talk was most revealing of students' chemical thinking to the teachers. The teacher with the wider noticing scope additionally used other sources, including students' annotated design drawings, prototypes and materials, and gestures. This is an encouraging finding, as blending evidence from multiple sources can allow teachers to draw more accurate inferences about students' thinking (Griffin et al., 2010). Still, we also noted unexploited opportunities for gaining insight in students' chemical thinking. For instance, the teacher who used design drawings paid attention to whether students had made a drawing or not, rather than what students had drawn or annotated (as advocated by, e.g. Roth, 1994). To explore the affordances of sources of information like students' annotated design drawings further, we conducted a detailed investigation into what these may reveal in the final empirical study of this thesis.

Chapter 5 reported on the study centring on the question: *How can design-authentic sources of information provide insight in students' use of conceptual understanding in chemistry in a design context?* This study sought to investigate affordances of design-authentic sources of information for gaining insight in students' understanding of chemistry concepts in a design setting. We examined chemistry students' talk within design teams, talk with the teacher participating in the conversation, and annotated design drawings. We selected the chemical thinking framework for analysis, as it acknowledges the significance of students' everyday and implicit ideas, and the contextual nature of student understanding (Sevian & Talanquer, 2014). This approach facilitated the characterisation of twenty five assumptions about the nature of chemical entities and processes as guiding students' thinking during design planning and drawing. Assumptions concerned a wide range of chemistry concepts (all six concepts of the framework), and different degrees of sophistication (i.e. involving more everyday or academic ideas). Whereas we found that all of the three consulted sources could reveal students' use of assumptions in the design context, the source revealing the greatest variety of assumptions differed between student teams. Use of an assumption was occasionally observable in only one of a team's sources of information (e.g. only in their annotated design drawing). These findings stress the importance of consulting and combining multiple design-authentic sources of information, and of paying attention to students' everyday and implicit chemistry ideas when pursuing insight into students' chemical thinking in a design context. Moreover, the findings demonstrate that design contexts can encourage students to activate a great variety of chemistry ideas, both in terms of their sophistication, and concerned chemistry concepts.

6.3 General discussion

By studying different matters of attention, this research sought to learn *what* insight in student learning teachers can gain in the complexity of design-based chemistry education, and *how*. The following sections provide an integrated discussion of the findings of the four studies.

6.3.1 What insight in student learning can teachers gain in design-based chemistry education

Research from the past decades has shown that engaging students in design-based science education offers a range of opportunities for student learning (e.g. Fortus et al., 2005; Kolodner et al., 2003). By studying matters of attention with a particular focus on the objects of that attention (Erickson, 2011), we aimed to understand what insights in student learning teachers can gain during design based chemistry education. We found that chemistry teachers may gain insight in a range of aspects of student learning in the multifaceted context of design. In the study presented in Chapter 3, for example, we found a chemistry teacher attending to students' developing chemical thinking, design practices and ownership in the course of a design-based chemistry project. The teacher furthermore gained insight in students' research practices, social interactions, behaviour and emotions. The study in Chapter 3 also demonstrated that a teacher's objects of interest can change through time (e.g. becoming more focused). We furthermore found that teachers may not necessarily gain similar insights in student learning in comparable design-based chemistry situations. The study in

Chapter 4 showed one teacher becoming aware of students' chemical thinking concerning a range of chemistry concepts while another's noticing was more narrow. Students' in both teachers' classes, however, used their understanding of a wide range of chemistry concepts when designing (as demonstrated in Chapter 5). Erickson (2011) also noted that there is variation in what different teachers notice. Afterall, teachers 'bring differing prior experience and differing pedagogical commitments to what they notice' (Erickson, 2011, p. 32). Our initial study (Chapter 1) had indeed revealed that the chemistry teachers in this research had different teaching and professional experiences, as well as different pedagogical ideas concerning design-based chemistry education.

Whereas studies in the field of teacher attention often zoom into specific objects of attention (e.g. Stockero et al., 2017; Talanquer et al., 2013; Watkins et al., 2021), this thesis provides a unique window into the range of insights teachers can gain in a design-based chemistry context. Capturing the multidimensional nature of teacher attention (i.e. the various objects that teachers attend to; Erickson, 2011) seems to be particularly important in design-based science settings. As Jessica Watkins and colleagues (2018) write: 'The openness of these challenges results in increased diversity of students' ideas, making teachers' tasks of attending and responding to student thinking more complex.' (p. 551). While these authors conducted their work in a design-based literacy setting, the study in Chapter 5 demonstrated that design-based chemistry education can also give rise to a wide range of student ideas, at least when students' ideas about chemical entities and processes are concerned.

Looking across the matters of attention investigated in this research shows that we have characterised objects of attention in design-based chemistry education at different levels of specificity (see Figure 6.1). At a large grain size level, we characterised teacher attention as revolving around major aspects of student learning including students' chemical thinking, design practices, social interactions, ownership and emotions (Chapter 3; building on work in Chapter 2). At a smaller grainsize, the research in this thesis asked what teachers do or could attend to within such an aspect of learning (Chapters 3, 4, 5). Concerning attention to students' design practices, for example, we found a teacher attending to students' engagement in and development of a variety of design practices, students' progress towards developing a successful design solution and students' design thinking (Chapter 3). And, attending to students' chemical thinking, for instance, was found to involve teachers' noticing of student ideas and reasoning about different chemistry concepts (incl. chemical identity, chemical mechanism, benefits-costs-risks; Chapter 4). The third, most specific level of observation concerned attention to details of student learning (Chapters 4, 5). Zooming in further on students' thinking about particular chemistry concepts, we could characterise teachers' attention at this level as involving particular student ideas. Regarding the crosscutting concept of chemical identity, for instance, we found a teacher noticing student understanding concerning the difference between conducting and insulating materials, the diversity of insulating matter types, the changing identity of matter during reactions, the thermal benefits of using matter, and more (see Chapter 4 for specifics, including the teacher's evaluation of those understandings). Figure 6.1 provides a visual overview of these three levels of specificity, and provides examples for each level. The diagram also highlights the multidimensionality of teachers' attention to student learning, which may thus be encountered at each level.

The diagram in Figure 6.1 not only provides an overview of findings in this research, but also offers a framework for positioning previous and future research in this emerging field of teacher attention. For example, the general level in the diagram also appears in work conducted by Van Es and M. Sherin (2008), and we can find an intermediate level characterisation of teachers' objects of attention in the study of Talanquer and colleagues (2013). Different levels of observation can have different affordances. Studies conducted at the general level have, for example, allowed researchers to capture teachers' shifting attention during a professional development intervention, seeing attention moving from classroom climate to students' disciplinary thinking (Van Es & M. Sherin, 2008). Research at the intermediate level has, for instance, shown what tangible sources of information can provide elementary teachers insight in certain research practices (Luna et al., 2018). And,

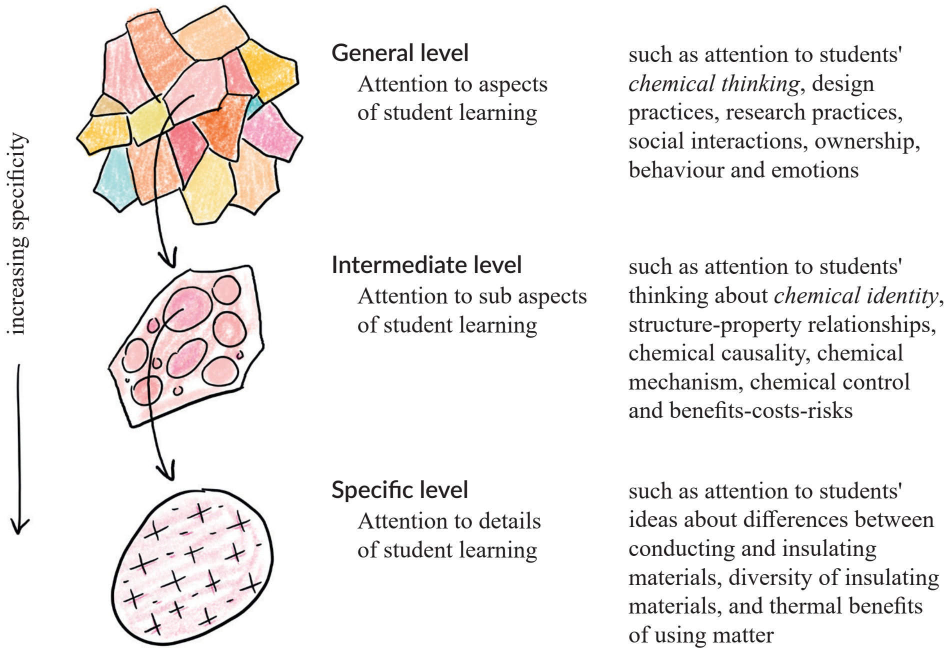


Figure 6.1. Characterising teachers' objects of attention at different levels of specificity. Examples on the right stem from findings in this thesis (general level, Chapter 3; intermediate level, Chapter 4; specific level, Chapter 4). The examples at the intermediate level concern a specification of attention to students' chemical thinking, and the examples at the specific level subsequently concern a specification of attention to students' thinking about chemical identity.

studies conducted at the specific level have revealed, for example, the value of learning progressions in supporting teachers to gain insight in details of student's thinking about natural selection (Furtak, 2012). The work in this thesis interestingly spans multiple of these levels of observation. As a whole, this research thus offers a rather comprehensive characterisation of attention to student learning in design-based chemistry education, particularly concerning attention to students' chemical thinking in design contexts.

6.3.2 How can teachers gain insight in student learning in design-based chemistry education

During instruction, teachers are faced with a 'blooming, buzzing confusion of sensory data' (M. Sherin et al., 2011a). As well as building understanding about what insights in student learning teachers can gain in design-based chemistry contexts (see the previous section), this research revealed facets of how such insight can be gained. We found that teachers can gain insight in student learning in design contexts by noticing student learning *in class* (Chapter 4), as well as by reflecting on classroom events and consulting tangible student artefacts in an *out-of-class*, dialogue-based setting (see Chapter 3 for examples). Findings additionally revealed the value of using students' talk, in addition to other sources of information (incl. annotated design drawings), when pursuing insight in students' chemical thinking in a design context (Chapters 4, 5).

This research's incorporation of multiple theoretical perspectives on attention to student learning seems to have helped us reveal this. Attention to student learning, involving processes of perception and interpretation, is central to several notions that are currently shaping the current educational landscape (see Russ, 2018). These include teacher noticing (M. Sherin et al., 2011a), and formative assessment (Black & Wiliam, 2009; Cowie et al., 2018). While each notion has particular affordances for revealing how teachers can gain insight in student learning, they are also isolated islands in some ways. For example, certain views on formative assessment neglect the full range of information that may be valuable to teachers (Shapiro & Wardrip, 2019), or do not make explicit in their models that elicited information on student learning also requires interpretation (see Black & Wiliam, 2009 for an example). A construct like teacher noticing does acknowledge the wealth of information available in classrooms as well as teachers' interpretation of that information (M. Sherin et al., 2011a). But, this second notion does not necessarily emphasise that the information in classrooms can be deliberately shaped to make particular aspects of student learning accessible to teachers. Carefully engineering activities to elicit student learning is, nevertheless, a key idea in formative assessment literature (incl. Black & Wiliam, 2009). In this research, we captured teacher attention in design-based chemistry contexts by conducting one study from a formative assessment perspective (Chapter 3), while drawing on teacher noticing in another study (Chapter 4). While each study was thus build around a focus construct, we also took care to incorporate key components of other relevant notions. For example, we included teachers' consultation and interpretation of a range of sources of evidence in the formative assessment study (Chapter 3). And, in the noticing study, we purposively chose and engineered design planning and drawing activities in order to help make students' chemical thinking accessible to teachers (Chapter 4). Since this approach allowed us to capture multiple interesting facets of teachers' attention to student learning, we suggest that others may similarly want to tap into these interrelated notions to advance their understanding. This argument is echoed by others in the broad field of teacher attention (Cowie et al., 2018; Furtak et al., 2016).

Our findings also give rise to the question whether using multiple sources of information could support teachers' insight in student learning when teaching in class as well as when consulting evidence in out-of-class situations. In the study presented in Chapter 4, we observed a teacher using multiple sources of information in class, and gaining a broad overview of students' chemical thinking (Chapter 4). The teacher also stated himself that connecting students' questions, a verbal source of evidence, to information, like students' design drawing, helped him make sense of students' thinking (Chapter 4). In out-of-class situations, teachers' access to sources of information is typically more narrow. Students' talk, expressions, gestures and actions are fleeting in nature (also see Lam & Chan, 2020). Tangible sources of information may more easily be drawn near for in-depth analysis by teachers in out-of-class situations (e.g. Chapter 3; Luna & Selmer, 2021). Still, videos of student interactions capturing different forms of evidence were found to provide teachers better access to the particulars of students' thinking than students' written work alone (Goldsmith & Seago, 2011). We also noted ourselves that just consulting students' annotated design drawings did not provide as much insight in students' chemical thinking as when combining this with students' talk (Chapter 5). Moreover, seeking insight in students' design practices, social interactions and emotions, for example, arguably calls for the use of sources of information ephemeral in nature, such as students' practical actions, gestures and facial expressions. This line of reasoning suggests that using multiple sources of evidence may benefit teachers' insight in student learning both within the classroom and in out-of-class, reflection situations. In addition to exploring how we may help teachers use multiple sources amidst the pressures of classroom teaching (as proposed in Chapter 4 and Lam & Chan, 2020), this argument seems to call for finding (low-key) ways for teachers to access such information outside of classroom constraints. Particularly as more in-depth analyses of student information can benefit teachers' professional development (Barnhart & Van Es, 2015). Concerning design-based chemistry contexts, students' annotated design drawing, notes and graphs, and prototypes may relatively easily be accessed out of class (as we saw in Chapter 3). To gather additional, ephemeral forms of evidence an option could be asking students to explain their design drawing or the results of a prototype test in a short vlog, for example.

6.4 Limitations and avenues for future research

The research presented in this thesis is qualitative and small-scale in nature. This setup proved successful in revealing features of attention to student learning in design-based chemistry education. Follow-up research is, however, desirable to verify these in other contexts, and to further probe teacher attention and its related constructs.

Studies could examine the multidimensional attention and evidence-use of more chemistry teachers, and in other design-based chemistry settings (e.g. during prototype testing or whole-classroom conversations). Afterall, teacher attention can differ between lesson contexts (Russ & Luna, 2013), and between teachers with varying experiences and ideas about teaching and learning (e.g. Erickson, 2011; Chapter 4). As design practices are an integral part of curricula of several science subjects, future research could also investigate teacher attention in these subjects (e.g. physics, biology as well as integrated STEM-subjects). Subsequent research efforts could furthermore study attention to student learning from additional angles. In the words of Stockero and Rupnow (2017), conducting their work from a teacher noticing perspective: '[…] measuring noticing in multiple ways is important, since different measurements and different units of measure give us different information about teacher noticing.' (p. 281). Other angles of relevance in science contexts include untangling attention processes (e.g. Jacobs et al., 2011; Santagata & Yeh, 2016), noticing for equity (Van Es et al., 2017), and the role of teachers' epistemological messages (Russ, 2018). However, as the research in this thesis underlines, such efforts should not neglect what teachers attend to. This research also highlights that capturing teacher attention in the complexity of design-based education does not only require acknowledging the disciplinary substance of teachers' attention (as in, e.g., Coffey et al., 2011; Watkins et al., 2018). Aspects of learning like students' social interactions, ownership and emotions are also relevant, as well as their possible connections within and across different levels of observation (also see Figure 6.1). Adopting a broader perspective has potential for revealing how teachers can (learn to) navigate different goals, which are so typical for design-based settings. Developing and using frameworks for characterising teachers' attention to different aspects of student learning does seem essential to facilitate such work (Nickerson et al., 2017; Chapter 4).

As well as attention itself as a topic for future investigation, we recommend further research into the relation between attention and other elements of teacher expertise in design-based chemistry education. Positioning the studies of this thesis along the continuum of teacher expertise as posited by Blömeke and colleagues (2015), shows what elements have been explored in this research (Figure 6.2). In the model, perception, interpretation and decision making are seen as the mediating processes between teachers' cognitions, beliefs and motivation on the one hand, and teachers' classroom practices on the other (Blömeke et al., 2015; Santagata & Yeh, 2016). This thesis's initial study into chemistry teachers' pedagogical ideas (Chapter 2), concerned the left side of this continuum as it entailed a characterisation of teacher cognition and beliefs. The studies in Chapters 3 and 4 focussed on teachers' attention to student learning, and thus fall in the middle of the model. One of these studies was conducted in an out-of-class context (i.e. reflection conversations; Chapter 3), another measured teachers' noticing in the heat of teachers' classroom (Chapter 4). As the second study was more closely related to teachers' classroom practice, we place it further to the right of the continuum. Through positioning the studies in this thesis with a focus on teachers (Chapters 2, 3, 4) along this continuum of teacher expertise, directions for future research become apparent. For example, chemistry teachers' classroom practices in design-based settings (right side of the continuum) was not a focus in this thesis. Based on a comparison of our findings in Chapters 4 and 5, we do recommend investigations into how teachers and students can engage in conversations in design-based chemistry classrooms that make student thinking visible and interpretable (see Roth, 1994 for an example in a physics classroom). Examining relations between facts of teacher expertise as presented in Figure 6.2 was also not a main focus of research in this thesis. Studies suggest, for example, that teachers may use as well as build pedagogical ideas when attending to student learning (e.g. Falk, 2012; Santagata & Yeh, 2016). What pedagogical ideas teachers activate or construct while attending to student thinking in design-based chemistry contexts still remains to be thoroughly examined.

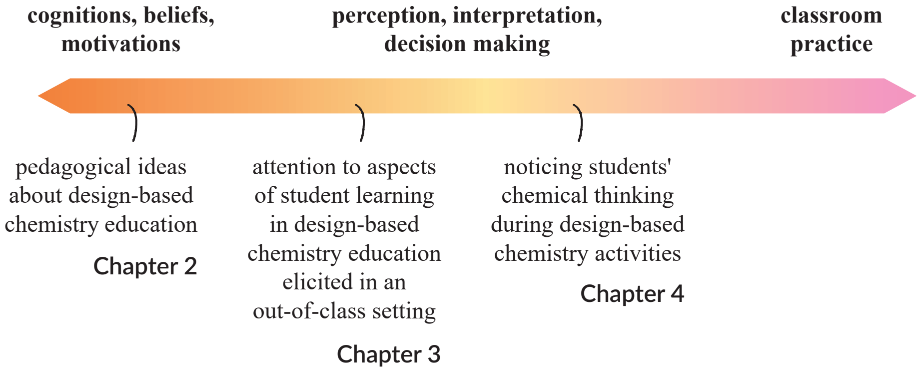


Figure 6.2. Positioning of this thesis' studies with a focus on teachers along a continuum of teacher expertise (model based on Blömeke et al., 2015; Santagata & Yeh, 2016).

Together, this line of research could interest those seeking to develop a comprehensive characterisation of teacher expertise in design-based chemistry education. Naturally, achieving this overarching goal would also require investigations into the development of such expertise, including development of teachers' attention to student learning. For example, we found that teachers may need support in understanding the role of design in the chemistry discipline (Chapter 1), and in attending to students' chemical thinking during design activities (Chapter 4). Instruments used in this thesis could aid efforts seeking to enhance teachers' attention to student learning. Recall, for instance, the adapted midstream modulation approach for reflection conversations (Chapter 3), and use of the chemical thinking framework to characterise attention to chemical thinking (Chapter 4), and to infer chemical thinking from design-authentic sources of information (Chapter 5). Furthermore, what may be characterised as productive attention – in other words, what attention matters – is still a topic of debate in educational research (see, e.g., Thomas, 2017). To come to definitions of productive attention to student learning in design-based chemistry settings, future research should seek to connect teachers' attention to student learning outcomes. The design-based chemistry projects developed iteratively in the context of this research's professional learning community, which include specific opportunities for making student learning accessible (Chapters 3, 4, 5), could facilitate such follow-up work. Findings presented in Chapter 5 additionally suggest that future investigations into development of students' chemical thinking in a design context may be aided by the use of multiple design-authentic sources of information, and the chemical thinking framework which acknowledges the relevance of students' everyday as well as more academic ways of thinking in a chemistry context (also see Sevian & Talanquer, 2014).

6.5 Practical implications

The studies in this thesis also yield suggestions for teachers and teacher educators (those who educate prospective and in-service teachers) regarding design-based chemistry education.

6.5.1 For teachers

This research draws focus to the importance of teachers gaining insight in student learning in the course of design-based instruction. For teachers, it is important to realise that a design context, with its open-ended and multifaceted nature, can prompt students to draw on a variety of ideas and practices (Chapter 5; also see Watkins et al., 2018; Wilson-Lopez et al., 2016). Some chemistry teachers may already be (implicitly) aware of this to some extent (Chapters 1, 2 and 3), while others may not. The diagram in Figure 6.1, which provides a characterisation of aspects of student learning that teachers may encounter, might serve as a tool for teachers to unravel some of the complexity of their students' learning in design-based chemistry education. It could also provoke teachers to consider or even add new objects of interest (also see Cowie et al., 2018), and pay attention to the details of student learning. Also, as teachers tend to have different objects of interest, and can value similar objects differently (Erickson, 2011; Chapter 4), the model might facilitate discussions between teachers about what attention to student learning matters to them or in their school regarding design-based chemistry education.

Regarding how teachers can gain insight in student learning, this research points to the potential of using multiple sources of design-authentic information (Chapters 4, 5). More traditionally used approaches to gathering information on student learning, such as through using content quizzes, can disrupt the authenticity and impact of a design-based context (also see Herrington et al., 2010). Regarding design drawings as a source of information, we did find annotations to be essential for our sensemaking of students' chemical thinking in a design context (Chapter 5). Teachers may thus want to ask students to add descriptions to their drawing (e.g. labelling elements; describing how and why the design could work), when planning to consult design drawings without access to an additional source (e.g. students' talk). Paying close attention to what students are saying also proved to be informative (Chapters 4, 5), highlighting the importance of providing a platform for students to (verbally) share their thinking during design-based education (practical examples can be found in, for instance, Kolodner et al., 2003 and Roth, 1994).

We saw that teachers can use information on student learning both in class (e.g. during conversations with design teams; Chapter 4), and out of class (e.g. when reflecting on classroom events; Chapter 3) to gain insight in student learning in a design context. Outside of the pressures of the classroom, information on student learning may be studied in more detail (also see, e.g., Barnhart & Van Es, 2015). Having limited access to sources of information, however, could constrain teachers' insight (Goldsmith & Seago, 2011). Teachers may thus also want to create opportunities that allow them to (collaboratively) study multiple forms of information after class to gain in-depth insight in their students' leaning. Teachers could, for example, ask students to make a short vlog during the lesson explaining their design drawing or the results of a prototype test.

This thesis additionally explored how design-authentic sources of information may be interpreted to reveal students' chemical thinking (Chapter 5). Research has shown that teachers use different ways to interpret information on student learning, including evaluating and inferring student thinking (e.g. Dini et al., 2020). Our study indicates that the inferential approach, where one seeks to see the sensibility in students' thinking rather than to assess thinking in light of canonical chemistry, may be particularly revealing in design contexts. Even though students may not use typical chemistry terms or canonical chemistry ideas when designing, we found that they may still be drawing (implicitly) on their understanding of a range of chemistry concepts. These can include more everyday ways of chemistry thinking (see Chapter 5 for a detailed characterisation). Afterall, design challenges do call on designer's intuition and imagination (Talanquer, 2013), and are typically tied closely to students' real world (Kolodner et al., 2003). Moreover, everyday chemistry ideas may actually be productively used in certain situations (Sevian et al., 2018). Paying attention to these ideas could thus help teachers gain insight in their students' chemical thinking in a design context.

The design projects developed in the context of this research (Expedition Toothpaste and the Thermo Challenge) could furthermore serve as a basis for Dutch chemistry teachers who want to engage their students in design. Particularly as they have been developed to encourage a teacher's attention to student learning by creating opportunities throughout the projects for students to share their thinking with teachers.

6.5.2 For teacher educators

In their seminal work on design-based science education, Janet Kolodner and colleagues conclude that teachers cannot always facilitate design-based science learning well right away, but 'if they have bought in to what could be in the classroom and if they have help as they are learning to implement the new approach, their classes thrive, and students and teachers learn together (even if teacher content knowledge and skills start off weak).' (p. 541; Kolodner et al., 2003). Given the affordances of a design-based approach to student learning in chemistry, which both researchers (e.g. Apedoe et al., 2008; Sevian & Talanquer, 2014), and chemistry teachers can be found to recognise (Chapter 1), we see an important role for teacher educators in supporting chemistry teachers in successfully implementing design-based approaches to learning in their classrooms. Drawing on the teacher expertise framework presented in Figure 6.2, and our research findings we make some recommendations.

Regarding teachers' cognitions, beliefs and motivation, we found that chemistry teachers can see design as a (potentially) valuable approach for chemistry education (Chapter 1). Teacher education efforts could draw on teachers' motivations for bringing design into their classroom, which can vary between teachers as we found, as a resource for professional development. We also noticed that this study's chemistry teachers, except those with a background as professional (bio)chemical engineers, did not see design as a typical chemistry practice, something that is in itself relevant in chemistry education (Chapter 1). This is in stark contrast with the nature of the chemistry discipline (see Talanquer, 2013), and current perspectives on meaningful chemistry education (Bulte et al., 2005; Sevian & Talanquer, 2014). Teacher educators addressing design may thus not want to do this just from a general science, technological or engineering perspective, but from a chemical one as well.

Regarding teachers' ability to perceive, interpret and make decisions regarding student learning in design-based classrooms, this research encouraging showed that in-service chemistry teachers may already have resources for attending to aspects of student learning in a design context (Chapters 3, 4). For refining teachers' attention to student learning in design-based contexts, our findings suggest that teacher educators may want to support teachers' sensemaking of a variety of (sub) aspects of student learning; use of multiple (design-authentic) sources of information to gain insight in student learning; and adopt an inferential approach to interpreting students' thinking. The teacher section above addresses these elements in more detail. This research also provides some initial suggestions for how teacher educators might support teachers' developing attention to student learning. The use of frameworks unravelling the 'how' of attention to student learning is a common practice to help (beginning) teachers develop their attention (see, for examples, Barnhart & Van Es, 2015 and Wiliam & Leahy, 2015). Teachers may similarly gain support from the use of a framework untangling possible objects of attention, such as the one in Figure 6.1. Perhaps even essential support, as focussing only on processes of attention (e.g. the teacher is or is not taking an inferential approach to interpretation) might not allow one to understand what insights in student learning a teacher actually gains (also see Coffey et al., 2011). The study in Chapter 3 additionally points to the value of engaging teachers in reflective dialogue to facilitate attention to learning. Such conversations can revolve around information on student learning, and involve multiple teachers (e.g. Barnhart & Van Es, 2015; Goldsmith & Seago, 2011). Or, perhaps even an (online) coach (see Watkins et al., 2021). Because of the mediating role of attention processes (see Figure 6.2), such activities might also help build teachers' pedagogical content knowledge, for instance (e.g. Falk, 2012), and support their classroom practice (e.g. Santagata & Yeh, 2016).

Teachers' classroom practice, the third facet of the expertise model, was not a focus of our research. However, drawing on the classroom settings of two of the studies in this thesis (Chapters 4, 5), we can highlight the importance of teachers' conversations with students in design-based science classrooms (also see Kolodner et al., 2003; Roth, 1994). Our studies suggest that students' thinking may more readily arise during conversations in one teacher's classroom than in another's (Chapters 4, 5). Helping chemistry teachers leverage conversations with students for interactive formative assessment purposes (Cowie & Bell, 1999; Dini et al., 2020) could thus be a topic of interest for teacher educators aiming to facilitate development of teachers' expertise in design-based education.

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Appendices

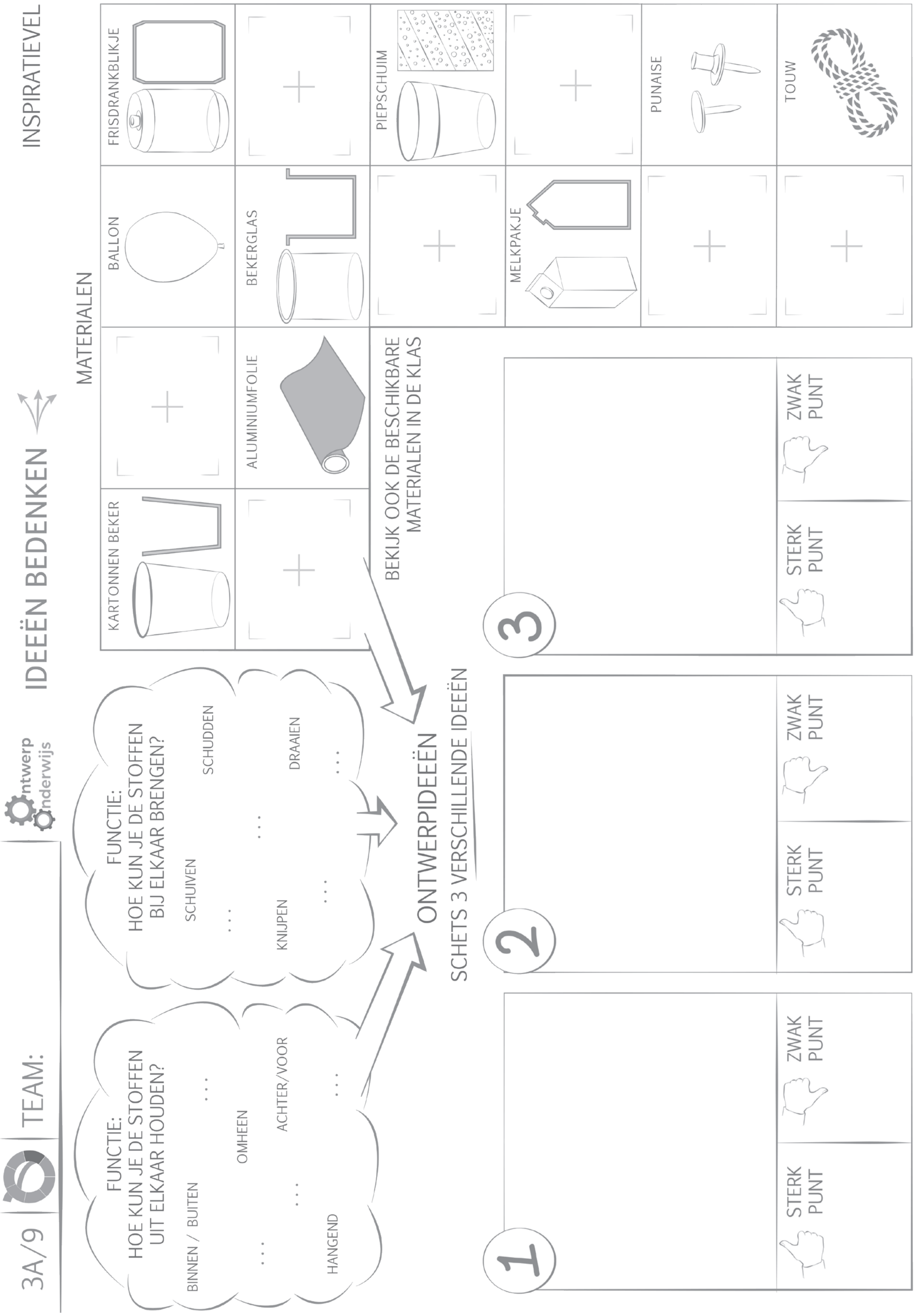
Appendix 1

Overview of activities of the Thermo Challenge design project. Data for the studies presented in Chapters 4 and 5 was collected in the context of the small-group design planning and drawing activities in lessons 3 and 7 (shown in italics).

	Student design activities
Lesson 1	Watching an introductory product video, formulating project questions based on the product's user instructions, participating in whole-classroom session on role of design in chemistry and design processes, playing and reflecting on an drawing game with the class, setting team's design challenge and requirements, drawing first ideas for design solutions
Lesson 2	Participating in whole-classroom session on reaction energy and heat, investigating endothermic or exothermic reactions in the lab, experimenting with amounts of reactants, recording observations, comparing results, justifying selection of reaction for the design
Lesson 3	Participating in whole-classroom session on estimating required amounts of reactants, comparing examples of design drawings and formulating success criteria with the class, *generating and drawing multiple design ideas, considering different materials and design functions, formulating pros and cons of ideas, deciding on a design, estimating required amounts of reactants*
Lesson 4	Constructing prototype, testing prototype, and recording observations and ideas for improving the design
Lesson 5	Constructing prototype, testing prototype, and recording observations and ideas for improving the design
Lesson 6	Participating in classroom session on reaction rate surrounding a demonstration experiment, investigating influence of different factors on reaction rate in the lab, recording and explaining observations
Lesson 7	Participating in classroom session on observations reaction rate experiments, sharing design problems and solutions with other teams, *evaluating team's prototype performance, generating ideas for improving the design, incorporating time aspect in design requirements, incorporating understanding of reaction rate in design, drawing design ideas and making design decisions, estimating required amounts of reactants*
Lesson 8	Constructing prototype, testing prototype, and recording observations and ideas for improving the design
Lesson 9	Creating the team's 'instructable', reflecting on design process, sharing the project's end products

Appendix 2

One of the design canvasses of lesson 3 of the Thermo Challenge design project (original is A3 size; see Chapters 4 and 5).



3A/9 | TEAM:

Ontwerp Onderwijs

IDEEËN BEDENKEN

INSPIRATIEVEL

FUNCTIE:
HOE KUN JE DE STOFFEN UIT ELKAAR HOUDEN?

BINNEN / BUITEN
OMHEEN
ACHTER/VOOR
HANGEND
...

FUNCTIE:
HOE KUN JE DE STOFFEN BIJ ELKAAR BRENGEN?

SCHUIVEN
SCHUDDEN
KNIJPEN
DRAAIEN
...

MATERIALEN

KARTONNEN BEKER
ALUMINIUMFOLIE
BALLON
BEKERGLAS
FRISDRANKBLIKJE
PIEPSCHUIM
MELKPAKJE
PUNAISE
TOUW

BEKIJK OOK DE BESCHIKBARE MATERIALEN IN DE KLAS

ONTWERPIDEEËN
SCHETS 3 VERSCHILLENDE IDEEËN

1
STERK PUNT
ZWAK PUNT

2
STERK PUNT
ZWAK PUNT

3
STERK PUNT
ZWAK PUNT

Appendix 3

Code list and descriptions of underlying assumptions identified in the design-authentic sources of information (see Chapter 5).

1	**What types of matter are there?**	
a	Normal matter classes	Matter belongs to one or more classes of ‘normal’, daily-life matter with certain characteristics (e.g. nails and wood are heavy; ice is cold; baking soda is non-poisonous).
b	Chemistry matter classes	Matter belongs to one or more classes of ‘special’, ‘chemistry’ matter with labels suggesting certain characteristics (e.g. metals can conduct heat and cold; matter called a substance can react; catalysts increase reaction rates).
c	Stable matter with features	Some matter has a property that can be turned on/off, shared and/or used up while the matter’s identity remains stable (e.g. ammonium chloride’s cooling property can be turned on or off by adding or removing water, ammonium chloride remains; there are substances which, once activated, produce heat infinitely).
d	Transformable matter	Matter’s identity can transform in certain conditions (e.g. plastic melts at high temperatures; some stuff dissolves when you add water).
e	Mixture matter	Matter can be a mixture of multiple matter types or substances (e.g. there is baking soda in the water; coffee consists of water and coffee stuff).
2	**What cues are used to differentiate matter types?**	
a	Daily-life use	How matter is used in daily life is a cue for differentiating matter (e.g. baking soda is used for making cookies so non-poisonous; aluminium is insulating because people feeling cold get wrapped in an aluminium blanket).
b	Perceivable properties	What matter looks like (e.g. colour; state of matter; size), feels like (e.g. weight; hardness) or tastes like (e.g. bad; like water) are cues for differentiating matter (e.g. liquids are just water; cold materials are metals; a filter with very tiny holes retains powdery substances but lets water pass through).
c	Chemistry labels	What names and formulas are used in chemistry contexts to label matter are cues for differentiating matter (e.g. citric acid is not sodium bicarbonate; metals are not plastics; calcium oxide is the same as CaO; ammonium chloride can be called a salt).
d	Response properties	How matter responds to certain (experimental) conditions are cues for differentiating matter (e.g. some matter dissolves in water; matter conducting heat well is a metal, not a plastic).
e	Components	What matter is composed of is a cue for differentiating matter (e.g. coffee has a water and a coffee stuff component, and is thus different from water).
3	**How do properties of matter types emerge?**	
a	Macro-particle properties	Macroscopic properties of matter are the same as the properties of matter’s constituting particles (when a drink is frozen its particles are also frozen).
4	**How does structure influence reactivity?**	
a	Grainsize	The grainsize of matter influences its reactivity (fine grained matter reacts quicker).

Appendix 3 continued

5	**What drives chemical change?**	
a	External change agent	Change is driven by a person bringing substances together, or by a change in surrounding temperature (e.g. after mixing ammonium chloride and water change just happens; a high temperature causes solid plastic to melt).
b	Active or enabling substance	Change is driven by an active substance acting on a passive substance, or by a substance enabling change between other substances (e.g. water initiates a reaction by acting on ammonium chloride which is just a powdery salt; water enables a reaction between citric acid and sodium bicarbonate).
6	**What determines the outcomes of chemical change?**	
a	Duration	The duration a change process takes determines its outcomes (e.g. when you are satisfied with the outcome you stop the reaction; after two minutes the temperature changed 12 degrees Celsius and it was still going).
b	Amount(s)	Amount(s) of starting substance(s) determine outcomes of a change process (e.g. a certain change in temperature requires a certain amount of starting substances; a smaller drink volume requires less substances for the endothermic process).
7	**What interaction patterns are established?**	
a	Contact	Change processes proceed because substances are in contact (e.g. when water and salt are mixed well, it becomes cold; the substances should touch).
8	**What affects chemical change?**	
a	Presence of substances	Change processes are affected by the presence of substances, specifically the concentration or amount(s) of starting substance(s), or the presence of a catalyst (e.g. the rate depended on whether a catalyst was added or not; the reaction rate differed depending on the concentration).
b	Level of contact	Change processes are affected by the level of contact between substances (e.g. if the stuff is up there and the water down there it doesn't work well; when we mixed it better, the temperature went down quicker).
9	**How can chemical change be controlled?**	
a	Adding substances	Change processes can be controlled by changing the presence of substances, specifically by increasing the concentration or amount(s) of starting substance(s), or by adding a catalyst (e.g. increasing 'concentration' by adding more of all substances; we'll add a catalyst to increase the reaction rate).
b	Increasing contact	Change processes can be controlled by changing (specifically increasing) the level of contact between substances (e.g. shaking the container more improves the process; using a more finely grained substance will increase the reaction rate).

Appendix 3 continued

10	**How can the effects be controlled?**	
a	Easy and enjoyable ways	Ways for controlling the effects of using matter can be thought of or decided on based on the perceived ease or enjoyment of using or designing a product (e.g. using a separate container for the reaction is no fun, let’s use a tea-filter approach; these calculations for amounts of substances are incorrect as the final product would be too heavy to carry).
b	Evidence-informed ways	Ways for controlling the effects of using matter can be thought of or decided on based on (weighing) identified effects, available data, information, calculations and/or chemistry knowledge (e.g. we’ll use the reaction that resulted in the maximum temperature change during the experiment; it’s smart to make the outside container from plastic as it doesn’t let go a lot of heat).
11	**What are the effects of using and producing different matter types?**	
a	User-personal effects	Benefits, costs and risks of using matter can be determined by taking the perspective of a product’s user and/or a personal perspective (e.g. you don’t want to hold a product that gets too hot; citric acid does not seem poisonous to me; I want it to get 4 degrees Celsius, let’s go for that).
b	Evidence-informed effects	Benefits, costs and risks of using matter can be determined by considering or gathering data, information, calculations or chemistry knowledge (e.g. when we used one gram the effect was halved; we should test whether this estimated rise in temperature is correct; a tea-filter would not prevent a user from consuming the substance if it dissolves).

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Curriculum Vitae

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2015 – 2016	Master Science Education and Communication resulting in an MSc degree and chemistry teacher qualification (first-degree qualification) master thesis titled ‘Ontwerponderwijs bij Scheikunde: Onderwijskundig ontwerponderzoek naar technisch ontwerpen als context voor het aanleren en verdiepen van vakconcepten’	Delft University of Technology
2011 – 2015	Bachelor Life Science and Technology resulting in a BSc degree and chemistry teacher qualification (second-degree qualification) bachelor thesis titled ‘A short chain 2,3-butanediol dehydrogenase: Its stereo-specificity and characterisation’	Delft University of Technology and Leiden University
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