Understanding Matter

A Review of Research on Students' Conceptions of Matter

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Abstract

This manuscript presents a systematic review of the research on how students conceptualize matter. Understanding the structure and properties of matter is an essential part of science literacy. Over the last decades the number of studies on students' conceptions of matter published in peer reviewed journals has increased significantly. These studies investigated how students conceptualize matter, to what extent students are able to explain everyday phenomena or how students develop an understanding of matter over time. In order to understand how students progress in their understanding of matter, what they understand easily and where they have difficulties, there is a need to identify common patterns across the studies at hand. Only then will we be able to guide students to a higher level of understanding. The first substantial review of research on students' conception was carried out by Andersson (1990) who developed a framework to organize students' understanding of matter into four categories: students' conceptions about 1) *chemical reactions*, 2) *physical states and their changes* 3) *atoms, molecules and particle systems* and 4) *conservation*. The aim of this piece of scholarship was to identify how subsequent research on students' conceptions of matter adds to this framework. Since the last comprehensive review of research on students' understanding of matter has been carried out in the early 2000s we analyzed studies on students' conceptions of matter published within the last decade in five peer-reviewed journals of science education. Our findings suggest that research has moved from categorizing students' conceptions to analyzing students' progression in understanding matter. Based on our findings we moreover identified typical pathways bay which students may develop over time related to the four categories identified by Andersson (1990). As a conclusion we present a model describing students' progression in understanding matter which may contribute to the development of a K-12 learning progression for matter.

Keywords: learning progression, chemistry, physics, conceptual change, matter

Introduction

Amongst all scientific concepts the concept of matter plays one of the most central roles for scientific literacy (Harrison & Treagust, 2002). On the one hand the atomic hypothesis is central to the construction of scientific ideas (Feynman, Leighton, & Sands, 1963). On the other hand an understanding of the structure and properties of matter is prerequisite for making informed decisions in everyday life for example when advertising suggests that new nano-based materials will indeed keep one save from rain whilst still offering enough venture. In addition understanding matter will provide a sound base for continued learning that will be necessary for future generations of scientists and non-scientists to grasp and potentially solve upcoming challenges such as shortage resources and the disposal of nuclear waste.

Although an understanding of matter is important for many reasons, research on students' understanding of matter has repeatedly and consistently shown that students' fail to obtain a deeper understanding of the particle nature of matter (Löfgren & Helldén, 2009; Nakhleh, Samarapungavan, & Saglam, 2005; Stefani & Tsaparlis, 2009; Talanquer, 2009). These findings indicate that students may not be prepared for the demands of today's world that is to act as informed citizens. Students' difficulties in understanding the concept of matter seem to stem from their experiences with matter in their everyday life (diSessa, 1988; Löfgren, 2009; Minstrell, 1992). These experiences lead to a variety of misconceptions that hinder the development of a proper understanding when students are taught about the particle nature of matter (e.g. Comber, 1983; Nussbaum, 1985; Pfundt, 1981; Stavy, 1989).

An initial categorization of the extensive research on students' everyday conceptions and the misconceptions that might emerge when students are taught about the particle nature of matter was undertaken by Andersson (1990). Andersson (1990) reviewed students' everyday conceptions about matter and its transformations (embracing students' conceptions about chemical reactions, physical states and their changes and conservation of matter) and students' conceptions about the particle nature of matter (embracing students' conceptions of atoms, molecules and particle systems). He concluded, that the majority of research is generally focusing only on identifying and describing students' misconceptions about individual aspects of the matter concept, but that there is a lack of studies investigated how students' understanding of matter develops with respect to the four aspects of matter (the particle nature of matter, chemical reactions, physical states and their changes and conservation of matter). Andersson's (1990) research had informed the direction of subsequent research on the topic of matter (e.g. Ahtee & Varjola, 1998; Bar & Galili, 1994; Benson, Wittrock, & Baur, 1993; BouJaoude, 1991; Gabel, 1993; Nakhleh & Samarapungavan, 1999; Stavy, 1991; Watson & Dillon, 1996). These studies provided further details regarding students' understanding of the four aspects of matter. However, these studies all focus on different aspects even within those four principle aspects of the concept of matter. As a consequence little is known about how students develop an understanding of those principle aspects and how to teach and improve students' understanding of matter as a core concept in which these different aspects are unified (Liu & Lesniak, 2005).

This manuscript details our efforts to systematize the findings from the research on students understanding of matter in the past decade. First, we argue that the open question is, how exactly students develop an understanding about each of the four aspects of matter by providing an overview of the decade post Andersson (1990). Then we will provide findings from a systematic review of studies concerning students' understanding of the matter concept in five leading science education journals over the past decade. Finally, from these findings we detail a framework which may serve as the foundation for further investigations according to students' understanding of the concept of matter.

Theoretical Background

The central question when asking about fostering students' understanding of matter is how do students ideally progress in understanding matter and individual aspects of matter such as its particle nature, the physical or chemical properties or the conservation of matter. Faced with the variety of studies aiming to elicit facets of students' understanding, Andersson (1990) grouped research on students understanding of matter up to the 90s into the following four categories: the particle nature of matter, chemical reactions, physical states and their changes and conservation of matter. Referring to Andersson's (1990) work, studies have been conducted focusing on students' understanding within a single category like physical properties and changes and conservation (e.g. Bar & Galili, 1994; Bar & Travis, 1991; Gómez, Pozo, & Sanz, 1995; Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993; Tytler, 2000; Watson, Prieto, & Dillon, 1997) or on chemical reactions (e.g. Ahtee & Varjola, 1998; Boo & Watson, 2001; Boujaoude, 1991; Hesse & Andersson, 1992). This body of research reveals that students develop an understanding within the different categories starting from a macroscopic towards a microscopic viewpoint of matter.

Despite the fact that most of these studies focused on students' understanding at a particular point in schooling, there are some studies which have taken into account the development of students' understanding across grades (Johnson, 1998; Krnel, Glažar, & Watson, 2003; Krnel, Watson, & Glažar, 1998; Renström, Andersson, & Marton, 1990). Renström et al. (1990) conducted an interview study with 20 students of ages 13 to 16 in order to elicit different conceptions of matter. Students were asked to explain phenomena that cover all of the four principle aspects of matter. Findings revealed that students held conceptions that could be assigned to the following categories: matter was understood to be 1) a homogeneous substance, 2) substance units, 3) substance units with „small atoms", 4) aggregate of particles, 5) particle units, and 6) systems of particles (Renström et al. 1990, p. 558). Renström et al. (1990, p.565) stated that these conceptions form a system of hierarchically ordered levels that describe a more and more sophisticated understanding of matter. Based on these findings, Johnson (1998) conducted a longitudinal study of 147 students of ages 11 to 15 in order to support Renström et al.'s (1990) findings with empirical evidence. Johnson (1998) indeed suggested that students develop an understanding of matter along the following sequence: 1) matter as a homogenous substance, 2) matter contains particles, 3) matter is composed of particles, 4) matter is composed of particles and the properties of matter depend on the interaction between particles. However, in his investigation the author focused only on phase transformations. Krnel et al. (1998) provided a review of existing literature, which suggests that students develop an increasingly complex understanding of the particle nature of matter. Students begin by accepting that matter is made of particles and then students proceed towards a more in-depth knowledge about the properties of those particles and how these properties relate to the properties of matter. Krnel et al. (1998) suggested that when understanding advances students are also able to provide more complex, in-depth explanations of physical properties of matter. Based on this review, Krnel et al. (2003, 2005) carried out a cross-sectional study of 84 students of ages 3 to 13. The authors concluded that students indeed develop an understanding of matter through the ability to differentiate between different kinds of materials and their properties (cf. Krnel et al., 2003, 2005) well in line with the findings of Nakhleh and Samarapungavan (1999) who interviewed 15 students of ages 7 to 10. In addition, Liu (2001) suggested that students' conceptions of matter may be described in two dimensions: existence of matter and properties of matter. The author stated described students' progression of understanding within these two dimensions by seven hierarchically levels that can be considered a more comprehensive description of the four levels suggested by Johnson (1998). Another approach to describe students' progression in understanding the concept of matter is suggested by Abraham, Williamson and Westbrook (1994). The authors conducted a cross-age study of 300 students from grade 9 to freshmen in order to investigate the influence of grade level and reasoning ability on the understanding of five chemistry concepts that cover the four principle aspects of matter. Five levels were used in order to describe students' understanding: (a) no understanding, (b) specific misconception, (c) partial understanding with a specific misconception, (d) partial understanding, and (e) sound understanding. Although students were found to develop a more and more sophisticated understanding of matter over time that could be described in terms of these levels, no inference could be drawn about what alternative conceptions students held in respective a specific level. That is, while students advance in their understanding over time, some alternative conceptions decrease, some increases and some don't change at all (cf. Abraham et al., 1994).

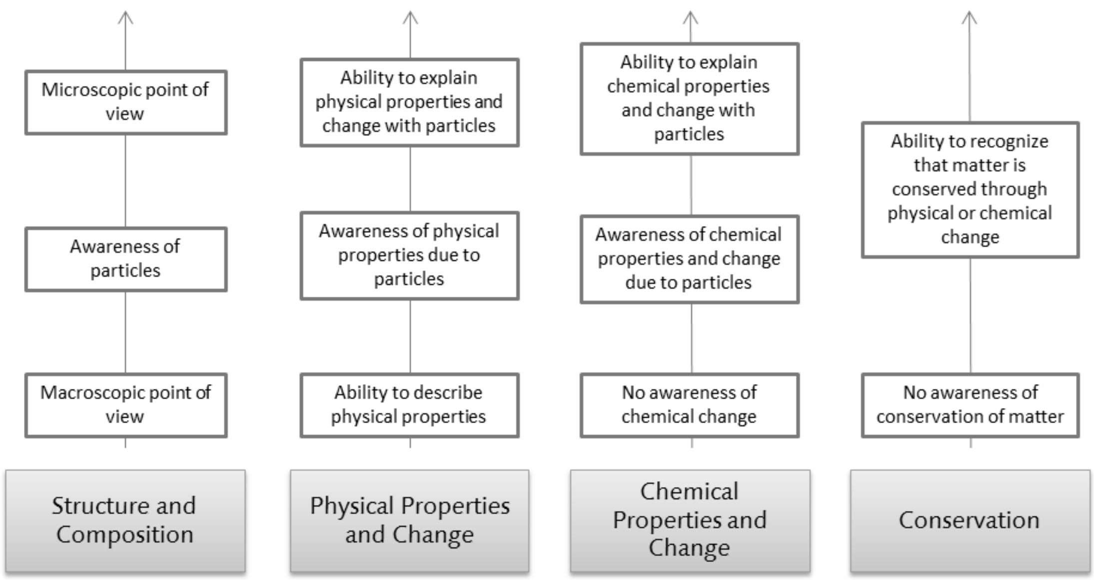

Figure 1. Pattern in students' progression of understanding the four aspects of matter (cf. Liu & Lesniak, 2006)

Reanalyzing the US TIMSS sample, Liu and Lesniak (2005) identified levels of students' progression for the following principle aspects of matter that can be considered an extension of Andersson's (1990) categories in order to better represent the extensive research on students' conceptions of matter (Liu & Lesniak, 2005 p.436): *structure and composition*, *physical properties and change*, *chemical properties and change* and *conservation*. The authors could show that students' understanding of matter develops from an understanding of physical properties and conservation, to understanding chemical properties, and finally advances to an understanding of the structure and composition of matter. However, the authors do not provide details about the way in which students progress in understanding the individual aspects according to the different sequences of levels described above. In a subsequent study, Liu & Lesniak (2006) expanded their findings by an interview study. Faced with different substances, students were first asked to describe the substances and second to describe what happens when these substances are combined (cf. Liu & Lesniak, 2006). The authors conclude that although for each substance different patterns in students' progression could be found and that there is a general movement from a macroscopic towards a microscopic understanding of the substances with a growing sensibility for the particle nature of substances as well as interactions between substances (Liu & Lesniak, 2006 p.340). Although these progression patterns are not tightly linked to a specific age or grade due to a big overlap in students' understanding, some information about how these patterns built on another is provided (see Figure 1).

In summary, past research suggests that the progression in understanding matter can be described through the progression in understanding individual aspects related to this concept and relations between those aspects. According to the nomenclature suggested by Liu and Lesniak (2005), previous research about students' understanding of matter suggests that students develop an understanding of matter through learning about the four principle aspects of matter: 1) structure and composition, 2) physical properties and change, 3) chemical properties and change and 4) conservation. This research also suggests that the progression of understanding matter can be described by some sequences of hierarchically ordered levels (see Figure 2).

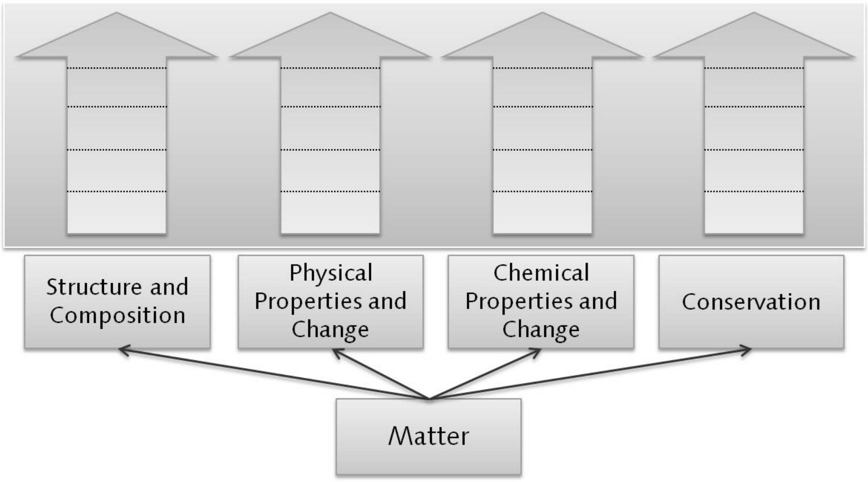

Figure 2: Understanding matter – Understanding four principle aspects of matter

However, there is no agreement about what facets of understanding students are expected to hold at a specific level. In addition, the majority of the above mentioned studies focused only on a selection of the four principle aspects. Under the heading of learning progressions some fruitful attempts have been made to describe students' idealized progress in understanding core concepts of science (Duschl, Maeng, & Sezen, 2011; Duschl, Schweingruber, & Shouse, 2007). Amongst learning progressions for the concept of matter there is some general consensus about how levels in this progression may look like (c.f. Black, Wilson, & Yao, 2011; Smith, Wiser, Anderson, & Krajcik, 2006; Stevens, Delgado, & Krajcik, 2010; Tsaparlis & Sevian, 2013). Nevertheless, there is no consensus about how these levels may look like in details. In order to work towards a “common set of levels” that take all of the four principle aspects of matter into account, there is a need to review not only research on learning progression, but research with a focus on students’ understanding of matter in general. Since Krnel et al.’s (1998) review of research on the development of the understanding of matter, Krnel et al.’s (2003) as well as Liu and Lesniak’s (2005) studies, numerous studies have been published that can potentially add towards an understanding of how students develop an understanding of matter (e.g. Adbo & Taber, 2009; Ayas, Özmen, & Calik, 2010; Johnson & Papageorgiou, 2010; Margel, Eylon, & Scherz, 2008; Othman, Treagust, & Chandrasegaran, 2008; Stefani & Tsaparlis, 2009; Stevens et al., 2010; Treagust et al., 2010; Tsitsipis, Stamovlasis, & Papageorgiou, 2010).

The aim of this study is to provide an systematic overview of the last decade of how research in the field of students’ understanding of matter has advanced – clarifying some issues, while raising new issues; in particular, how this research relates to the somewhat established view that an understanding of matter is developed through an understanding of the four principle aspects and what this research can clarify toward an understanding of how students’ understanding is developed. The specific research questions are:

1. To what extent does the research of the past decade align with the four principle aspects 1) structure and composition, 2) physical properties and change, 3) chemical properties and change and 4) conservation of matter?
2. To what extent does the research of the past decade add to what we know about how students’ progress in understanding matter with respect to the four principle aspects of matter?

Methods

In order to provide a detailed overview of research related to students’ conceptions of matter in the past decade, we performed a systematic literature following the approach suggested by Bennett, Lubben, Hogarth, & Campbell (2005). This approach defines a sequence of four steps to be completed for a systematic literature review: 1) developing criteria for search strategies, 2) characterizing the articles that build the foundation of the review, 3) providing an overview of the articles and 4) reporting details of specific aspects of studies. This approach has been successful applied in various contexts (e.g. Bennett, Hogarth, & Lubben, 2005; Hogarth, Bennett, Campbell, Lubben, & Robinson, 2005; Lee et al., 2011; Taskin & Bernholt, 2012) in order to avoid a kind of “narrative” review (Bennett et al., 2005), but to support the community with reproducible, clear structured and (in terms of the applied inclusion or exclusion criteria information) complete information that meet the focus of the review (Bennett et al., 2005).

Criteria for Selection of Studies

The concept of matter is probably one of the most studied concepts in students’ conceptions research (Liu, 2001; Talanquer, 2009). Accordingly an extensive body of literature has been created until today. For a review to be completed in reasonable time and with reasonable effort, it is necessary to focus on a particular time span and a selected number of scientific outlets. The latest study that focused on students' progression of understanding related to all of the four principle aspects of matter explicitly was undertaken by Liu and Lesniak (2005). As the authors took into account research up to 2003 (e.g. Coll & Treagust, 2003; Krnel et al., 2003) the timespan from 2003 up to 2012 – one decade of research on students' conception of matter – can be considered a reasonable time span for this review. But even if we focus our review to research of the past decade, hundreds of pieces of scholarship that have contributed to what we know about students' conceptions of matter need to be taken into account. For this reason, it's almost impossible to review and locate all articles, book chapters, proceedings that are available. Therefore we decided to restrict the body of literature for this review to published articles in the most relevant, high-quality journals. Therefore we focused on journals with an impact factor 2012 > 1.0 that are peer-reviewed and widely distributed within an international community, contributing a significant amount of studies about students' conceptions, namely: *Journal of Research in Science Teaching, International Journal of Science Education, Science Education, Studies in Science Education, Research in Science Education*. First, titles and abstract of the 2777 articles published in these journals from 2003 to 2012 were screened by two researchers in order to exclude articles that do not focus on the concept of matter. 124 articles remained for further analysis and were read more closely. Second, articles that only focused on student teachers, in-service teacher, university students, adults or the analysis of textbooks were excluded. 82 articles remained and were considered as base for this systematic review.

Characterization of Studies

The articles that remained after applying the criteria described above provide a rich picture of different facets of science education research related to the concept of matter. There are studies focusing on students' understanding of chemical bonding (e.g. Coll & Treagust, 2003; Hilton & Nichols, 2011; Taber, Tsaparlis, & Nakiboğlu, 2012), on the relationship between students' understanding of different aspects (Cakmakci, Leach, & Donnelly, 2006; Crespo & Pozo, 2004; Othmann et al., 2008), on understanding materials (Acher, Acár, & Sanmartí, 2007; Krnel et al., 2005; Margel et al., 2008) or on the impact of instruction in order to foster students' understanding of matter (e.g. Adadan, Trundle, & Irving, 2010; Ardac & Akaygun, 2004; Nahum, Mamlok-Naaman, Hofstein, & Krajcik, 2007), even understanding of matter hold by congenial blind students are reported (Smothers & Goldston, 2010). In order to address the two research questions (focusing on the four principle aspects and how students' progress in understanding matter in respective these aspects), we categorized the studies in two ways: first, it was investigated for each study, which aspects of matter were addressed, second, for each study the span of age or the ranges of grade bands students were drawn from was identified. The latter one was to gather information about the extent the design of each study allows to draw one's conclusions in regard of students' progression of. In order to be able to draw interference to what extent the findings from these studies are supported by empirical evidence, the number of participants was also identified. An excerpt of the categorized studies is presented in Table 1. This categorization of articles was carried out by two researchers independently from each other. In 97 % of all 328 cases (4 aspects, 82 studies) the researchers agreed in their assignments.

Table 1. Excerpt of the studies analyzed in this review (for full table see Appendix)

Study	Number of Participants	Grade band / age	Aspects of Matter			
			SaC	Phy	Che	Con
Löfgren and Helldén (2009)	23	age 7 – 17	X	X	X	X
Krnel et al. (2005)	84	age 3 – 13	X	X		
Talanquer (2009)	(review)	K – 12	X	X	X	
Kermen and Méheut (2011)	144	grade 12	X	X	X	
Salta and Tzougraki (2011)	624 / 499	grade 7 & 9	X	X	X	X
Cokelez (2012)	76 / 50	grade 6 & 7	X			

Sac: Structure and Composition, Phy: Physical Properties and Change,
Che: Chemical Properties and Change, Con: Conservation

Findings

Following Bennett et al. (2005) we present the findings from our systematic review of research on students' understanding of matter by first, providing an overview of the studies from 2003 to 2012 in the selected journals. Then we present a synthesis of levels in order to characterize students' understanding of matter in general. Finally, we provide specific findings in order to detail these levels of understanding in respective the four aspects of matter: structure and composition, physical properties and change, chemical properties and change and conservation.

Students' progression in understanding matter – a bird's eye perspective

Overall, in the period from 2003 to 2012 4 reviews, 5 longitudinal studies as well as 73 studies that used a cross-sectional design (33 with respect to multiple grades and 40 with respect to a single grade - see Table 2 for details) were published in the five target journals (see previous section). All of these studies focused on details of the structure and composition aspect of matter. In addition, these studies focused 62 times on an understanding of its physical properties and change, 37 times on chemical properties and change and 37 times on conservation aspects (see also Table 2). In summary, most studies (27) investigated students' understanding related to three of the four principle aspects of matter. But also two aspects (25 studies focusing mainly on physical properties and change and structure and composition) and four aspects (19 studies) were covered (see Table 2).

Table 2. Overview about the body of literature

Year	Research Method				Aspects of Matter				Number of Aspects			
	Review	Longitu-dinal	Multiple Grades	Single Grade	SaC	Phy	Che	Con	1	2	3	4
2003	0	0	7	2	9	4	2	1	4	4	0	1
2004	1	0	1	3	5	4	2	2	1	2	0	2
2005	1	1	4	5	11	11	6	5	0	2	7	2
2006	0	0	3	1	4	4	2	3	0	0	3	1
2007	0	1	4	3	8	6	4	3	1	3	2	2
2008	0	2	2	3	7	3	3	3	2	2	2	1
2009	1	1	5	6	13	11	6	8	1	3	5	4
2010	1	0	5	7	13	10	7	7	1	4	4	4
2011	0	0	2	3	5	5	2	3	0	1	3	1
2012	0	0	0	7	7	4	3	2	1	4	1	1
Over-all	4	5	33	40	82	62	37	37	11	25	27	19

Having identified the different aspects that have been investigated within the studies, the next step was to identify studies that have the potential to elicit big stepping stones of students' progression in understanding matter. Therefore, studies that cover a broad span of time were analyzed (that is, studies with participants drawn from five or more different grades between K – 12 or reviews that cover a comparable span of time – see Table 3).

Table 3. Studies with a focus on students' understanding of matter across five or more different grades or ages

Study	Grade band or age	Aspects of Matter			
		SaC	Phy	Che	Con
Ferk et al. (2003)	age 13-14, 17-18 and 21-25	X			
Krnel et al. (2003)	age 3,5,7,9,11 and 13	X	X		
Crespo and Pozo (2004)	grade 7,9,11 and university	X	X	X	X
Krnel et al. (2005)	age 3,5,7,9,11 and 13	X	X		
Liu and Lesniak (2005)	grade 3,4,7,8 and 12	X	X	X	X
Gómez et al. (2006)	age 9-22	X	X		X
Liu and Lesniak (2006)	grade 1-10	X	X	X	X
Talanquer (2009)	grade K - 12	X	X	X	
Mohan et al. (2009)	grade 4, 6-12	X	X	X	X
Löfgren and Helldén (2009)	age 7-17	X	X	X	X
García Franco and Taber (2009)	grade 7-11	X	X	X	X
Stevens et al. (2010)	grade 7 to 14	X	X	X	
Smothers and Goldston (2010)	grade 6,7,9 and 11	X	X	X	X

Findings from Liu & Lesniak (2005, 2006) as well as Krnel et al. (2003, 2005) are not reported in this section as these studies have been already considered in the theoretical background. Findings from Ferk, Vrtacnik, Blejec, & Gril (2003) are not reported either because the focus of that paper was solely on students' understanding related to 3D molecular models.

The broadest span of time is covered by Talanquer (2009), who's findings are subsumed in the following, suggested a set of dimensions in order to describe students' growth in understanding matter. Each dimension is characterized by unique assumptions that may hinder students to develop a sound understanding of matter. Like in Liu and Lesniak's (2006) work, students are found to develop an understanding of the structure of matter starting with the assumption that all substances are continuous, followed by the assumption that small particles are embedded in substances towards an understanding that substances are made of particles. Students start to perceive these particles as something that is static has the same properties as the substance until they recognize that the properties of a substance are due to the interaction between dynamic particles. Thus changes in properties are at first not perceived as changes in the interaction between particles, but as changes of the properties of specific particles inside the substance. First, students may assume that these interactions can only occur, when particles meet, followed by the assumptions that these interactions can be influenced by various factors (e.g. temperature). Finally, students may recognize that the strength of these interactions is due to the distance between particles (cf. Talanquer, 2009).

In contrast to Talanquer (2009), other studies on students' progression in understanding matter (see Table 3) offer sets of clearly defined levels along which students are supposed to progress while advancing in their school-career. Smothers and Goldston (2010) classified blind students' understanding of matter by two categories: a macro-particulate and micro-particulate understanding. That is, students refer mainly to observable properties or invisible particles inside matter when they are asked to explain different kinds of phenomena. In line with Smothers and Goldston (2010) two systems of levels were utilized by a similar set of levels was applied by García Franco and Taber (2009): (0) no explanation, (1) no notion of particles in students' explanations, (2) particles used in a non-scientific way, (3) particles used in a scientific way. Löfgren and Helldén (2009) utilized an extension of these levels in a ten-year longitudinal study, starting again with students' macroscopic point of view and ending with an understanding of particles that can be considered scientifically correct. In contrast to García Franco and Taber (2009), two levels of understanding that can be considered scientifically incorrect are utilized. That is, (a) students use scientific terms or facts in a non-productive way and (b) students use an undifferentiated particle concept in a productive way, but these particles may be for example embedded in the substance (cf. Löfgren & Helldén, 2009). A further elaboration of these levels is provided by Gómez, Benarroch, & Marín (2006) who focused on the degree of coherence found in students' conceptions of the particulate nature of matter and suggested a set of five hierarchically ordered levels to characterize differences in students' understanding starting from a simple towards a complex understanding. In line with Löfgren and Helldén (2009) the authors identified two levels of understanding in which students are expected to perceive particles in a non-scientific way, that is, (a) matter is stuffed with particles or gaps and (b) matter is made of particles to which macroscopic properties are transferred (cf. Gómez et al., 2006). Furthermore, the authors identified two levels that allow students to explain certain phenomena in a scientifically correct way, that is, (a) students perceive a vacuum between particles and (b) students perceive a causal coordination between vacuum and movement of particles. Crespo and Pozo (2004) analyzed student's understanding in respective physical and chemical change of matter: changes of state, expansion, solutions and chemical reactions. Students were given a set of multiple choice items with response options corresponding to the following conceptions: *transmutation, displacement, attribution of macroscopic properties* and *kinetic model*. The authors were able to show that the choice of response options that are related to the first three conceptions decreases, while the choice of response options that reflects a kinetic model increases over time (cf. Crespo & Pozo, 2004).

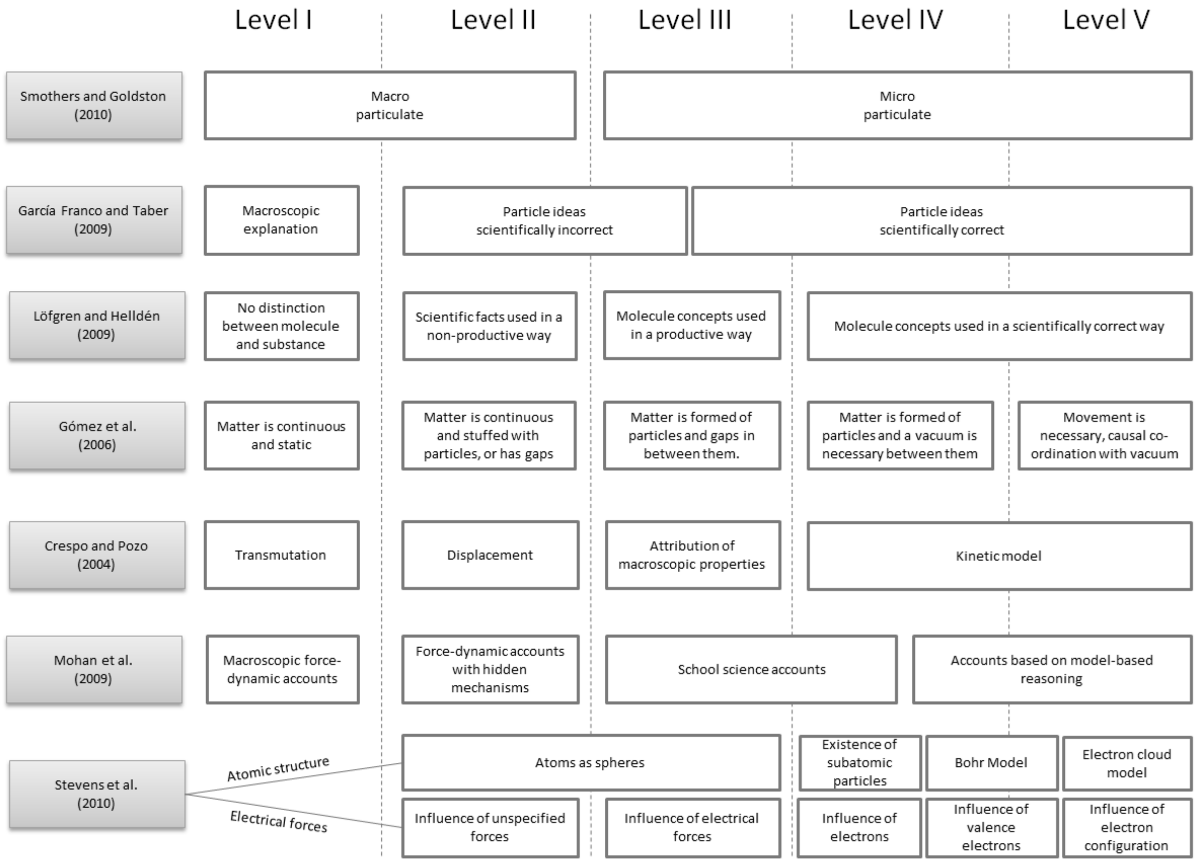

Figure 3. A comparison of levels used to describe students' progression in understanding of matter

Two studies focused on the development of learning progression related to the concept of matter, namely students' understanding of carbon-transforming processes (Mohan, Chen, & Anderson, 2009) and students' understanding of the nature of matter in relation to nanoscale science and engineering (Stevens et al., 2010). Mohan et al. (2009) were able to identify four hierarchically levels in order to describe students' ways to a more elaborated understanding of these processes. Again, students seem to held a naïve view at the beginning of schooling (level 1), which is followed by the perception that matter changes in terms of hidden mechanisms (level 2) or chemical reactions involving atoms and molecules (level 3). Finally, students are capable to apply sophisticated models that allow them to describe macroscopic, observable change by changes in the submicroscopic scale (level 4 – cf. Mohan et al.). Focusing on matter at nanoscale, Stevens et al. (2010) identified two sets of levels in order to describe students' progression in understanding the atomic structure and electrical forces. In contrast to the levels presented above, the perception of atoms as spheres with an unspecific force causing interactions between them is suggested as a starting point. Students are expected to advance in their understanding of the atomic structure by perceiving that atoms are made of protons, neutrons and electrons that can be described in terms of the Bohr model or the electron cloud model (cf. Stevens et al., 2010). In regard of understanding electrical forces, students become more and more able to understand how an atom's electrons determines its possibilities to interact with other atoms (cf. Stevens et al., 2010).

A comparison of these sets of levels reveals some commonalities (see Figure 3): Overall, students seem to start with a naïve view of matter characterized by their daily life experience, explaining phenomena as they were observed, without any notion of particles (naïve concepts – level 1). Perceiving the existence of particles, students are getting confused and are not able to apply new terminology in a scientific correct way, for example they might perceive that particles are embedded in substances (Hybrid concepts – level 2). Although perceiving that matter is built by particles and being able to apply a simple particle model in order to explain phenomena related to the four aspects of matter, students are not familiar with this new explanatory scope and are typically found to held specific misconceptions like attributing macroscopic properties to the particles (simple particle concepts – level 3). Understanding the nature of these particles, that is, that these particles are actually made of particles themselves, students are able to apply a differentiated particle model for explaining a variety of phenomena in a scientifically correct way (differentiated particle concepts – level 4). Finally, students are able to draw on their elaborate understanding of how properties of particles and of particles systems contribute to the macroscopic observable properties of a substance (systemic particle concepts – level 5). This level can be viewed as a transition level between K-12 education and further education (e.g. college or university), as only few students were found to held such understanding at the end of schooling (e.g. García Franco & Taber, 2009; Gómez et al., 2006; Löfgren & Helldén, 2009; Stevens et al., 2010). Although the number of levels used in the past in order to describe students' progress in understanding ranges from two or three (Liu & Lesniak, 2006; Talanquer, 2009) to five (Gómez et al., 2006) or seven (Liu, 2001 – see theoretical background) these five levels seem to form a basic consensus between different approaches to characterize students in getting more and more experienced with matter and its relation to particles. As this set of levels is derived from research that cover (a) a broad span of time and (b) covers all of the four principle aspects of matter (structure and composition, physical properties and change, chemical properties and change, conservation) it is safe to say that this set of levels can be considered a "basic" model to describe students' progression in understanding matter (see Figure 4).

It needs to be pointed out that students are not on a one-way-road towards expertise while advancing in their school career. In contrary, the studies from which this model is derived provide evidence that students' understanding is specific on task or context (Crespo & Pozo, 2004; Gómez et al., 2006; Smothers & Goldston, 2010). We will enlarge this rudimentary model in the following section in order to provide details of students' understanding related to the four aspects of matter.

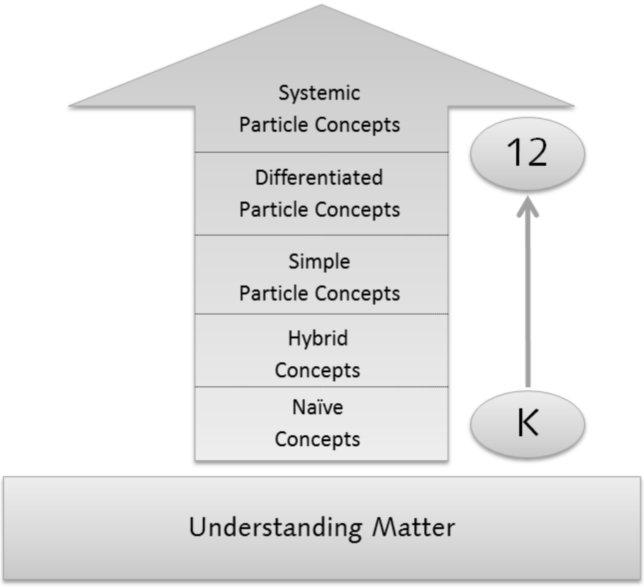

Figure 4. A skeleton of students' progress in understanding matter.

Students' progression in understanding matter – details in respective the four aspects

What one gains in general, one loses in concreteness and fine detail. (Andersson, 1990, p. 54)

In the previous section we selected studies in terms of their potential to provide a general picture of how students' progress in their understanding of the concept of matter. An analysis of these studies led to a skeleton (see Figure 4) of five levels in order to describe students' progression of matter in general. There is strong evidence that these levels can be used as means to describe students' progress of understanding with respect to the four principle aspects of matter (see Table 3). But what this model obscures is how exactly students develop an understanding of these aspects, that is what are the differences and commonalities of, for example, hybrid concepts with respect to *conservation* and *physical properties and changes*. In the following we detail our findings with respect to students' progression in understanding these four aspects of matter taking the pieces of scholarship into account that focused on either fewer aspects or a shorter span of time as the studies in the last section did. For each of the aspects our analysis starts with a description of students' understanding related to level 1 (naïve concepts) and ends with a description of students' understanding related to level 5 (systemic concepts). A more detailed description of students' idealized progression within the four principle aspects can be found in the supplemental information.

Structure and Composition

Level 1: Students describe structures without the use of the particle concept (Liu & Lesniak, 2006). They consider matter as dividable but continuously build (Ayas et al., 2010; Papageorgiou, Grammaticopoulou, & Johnson, 2010). *Level 2:* Students understand particles as entities embedded in matter (Johnson, 2005). Between the particles is the actual substance (Papageorgiou et al., 2010; Talanquer, 2009; Tsitsipis et al., 2012). Students are not able to use their perception of particles to explain the structure of matter (Johnson & Papageorgiou, 2010).

Level 3: Students understand particles as a building brick of matter (Johnson & Papageorgiou, 2010; Nakhleh et al., 2005). There is nothing between the particles. These particles are often described as the "last divisible unit" that is why they are often described with macroscopic properties (Adadan et al., 2010; Gómez et al., 2006). *Level 4:* Students are able to describe particles with the use of a differentiated atom model (e.g. nucleus-shell, shell model) (Adbo & Taber, 2009). They differentiate between atoms and molecules and can distinguish between different bond types (Gómez et al., 2006; Löfgren & Helldén, 2009; Othman et al., 2008; Smothers & Goldston, 2010). *Level 5:* Students are able to describe and to explain the structure of complex molecules (Urhahne, Nick, & Schanze, 2009). They are able to explain why specific interactions in a system of particles occur. (Stevens et al., 2010).

Physical Properties and Change

Level 1: Students do not have any model that allows them to describe physical properties and changes of matter scientifically. They describe only what they have observed (García Franco & Taber, 2009; Liu & Lesniak, 2006). They use prototypes to describe substance properties, e.g. water is a prototype for liquids (Krnel et al., 2005; Othman et al., 2008). *Level 2:* Students are able to categorize substances and to attribute characteristic properties to these categories (metals, non-metals, salts), therefore students use "actions" or "similarities" to classify substances and matter (Krnel et al., 2005). Students describe physical changes as modification of the original substance without using the particle model for a reasonable explanation (Krnel et al., 2005; Smothers & Goldston, 2010). Particles that are embedded in matter are often used in explanatory approaches (Ayas et al., 2010). *Level 3:* Students describe physical properties and changes with the use of a simple particle model (García Franco & Taber, 2009; Löfgren & Héllden, 2009;). They transfer the substantial properties and changes to the particle level (García Franco & Taber, 2009; Löfgren & Helldén, 2009;). *Level 4:* Students are able to use a differentiated particle model to explain physical properties and changes of matter (Johnson & Papageorgiou, 2010; Pimthong et al., 2012). Thereby, they dwell especially on the atom structure and the different interactions between atoms (Adadan, Irving, & Trundle, 2009; Smothers & Goldston, 2010; Stevens et al., 2010; Talanquer, 2009). *Level 5:* Students are able to trace physical properties of matter and conditions for physical changes back to the properties of particle collectives (Johnson, 2005; Johnson & Papageorgiou, 2010; Papageorgiou et al., 2010; Salta & Tzougraki, 2011).

Chemical Properties and Change

Level 1: Students do not have any model that is appropriate to describe or to recognize chemical reactions scientifically. In explanation approaches, they describe what they have observed (García Franco & Taber, 2009; Smothers & Goldston, 2010). *Level 2:* Students recognize chemical reactions through the emergence of a new substance with other properties than the reactants (Liu & Lesniak, 2006). As they do not have a particle perception in order to explain chemical reactions correctly, the following misconceptions appear frequently: (a) students claim that the products of a chemical reaction were already present in the reactants (Krnel et al., 2005; Papageorgiou et al., 2010), (b) students claim that the reactants are still present but only their properties have changed (Krnel et al., 2005; Smothers & Goldston, 2010), (c) students do not recognize the coherence between educts and products. The educts have changed to a new substance or to energy (Kermen & Méheut, 2011; Liu & Lesniak, 2006; Smothers & Goldston, 2010). *Level 3:* Students describe a chemical reaction as reorganization of particles. But they have no model which allows them to describe processes during a chemical reaction (Crespo & Pozo, 2004; García Franco & Taber, 2009; Papageorgiou et al., 2010). *Level 4:* Students describe a chemical reaction as reorganization of particles and bonds (Mohan et al., 2009; Rahayu & Kita, 2010). In doing so, they are able to describe elementary reactions on the basis of a differentiated particle model and to name bond types in the products of a chemical reaction (Liu & Lesniak, 2005). *Level 5:* Students are able to name factors that help them to explain the behavior of reactions of a substance (e.g. electron configuration) (Adbo & Taber, 2009). They are able to justify possible reaction progresses by taking a variety of influencing factors into account (pressure, temperature, structure of all participating substances in the reaction) (Treagust et al., 2010).

Conservation

Level 1: Students do not observe any conservation of mass in their daily life. They believe that the number of reactants changes with the mass in a chemical reaction for they do not have any particle perception (Löfgren & Helldén, 2009). Thus, substances can disappear in chemical reactions and in physical changes (Mohan et al., 2009; Rahayu & Kita, 2010; Smothers & Goldston, 2010). *Level 2:* Students understand that substances cannot disappear and that the number of particles has to remain constant in chemical reactions or physical changes (Liu & Lesniak, 2006; Pimthong et al., 2012). Students believe that the mass of a substance depends on the position and on the aggregate state of a substance (Othman et al., 2008). *Level 3:* Students are able to use the principle of conservation of matter as well as the principle of conservation of the amount of particles in a scientifically correct way (García Franco & Taber, 2009; Mohan et al., 2009; Rahayu & Kita, 2010). *Level 4:* Students are able to use the concept of conservation of energy for a chemical change (Mohan et al., 2009). Therefore, they make use of their knowledge about different bond types and interactions (Mohan et al., 2009). *Level 5:* Students are able to use energy and matter concepts to describe conservation for example by including laws of thermodynamics in their explanations (Taber, 2005).

Discussion

The overarching aim of this review was to elicit what research conducted in the last decade adds to what we know about how students' progress in their understanding of matter with respect to the four principle aspects of matter (Figure 1). The following two questions were used to guide our investigation: 1) To what extent research of the past decade aligns with the four principle aspects of matter (*structure and composition*, *physical properties and change, chemical properties and change* and *conservation*); 2) What is the "state of the art" in terms of what we know about how students' progress in understanding the concept of matter with respect to the four principle aspects.

With respect to the first research question, our findings provide evidence that the four principle aspects can still be applied – like Andersson (1990) did in his work – in order to structure studies on the concept of matter and to characterize students' conceptions in respective. These aspects are well covered by the focus of the research in the past decade with an emphasis on the physical properties and changes of matter (see Table 2). In regard the following statement, expressed around seven years ago

> *little has been reported on students' conceptions of matter as a unifying theme involving various aspects of matter. (Liu & Lesniak, 2006, p. 321)*

one needs to say that research in the past years moved massively forward towards investigating students' understanding of matter taking a variety of aspects of matter into account (see supplemental information). Although the four principle aspects have seldom been addressed in terms of the same terminology as in this study, it was manageable to subsume the variety of aspects with the help of these four aspects.

Referring to the second research question, one can say that the picture researchers are able to draw in respect of students' facets in understanding matter has become much more elaborated during the past decade. As a result, strong evidence could be provided that students' understanding of the four principle aspects of matter is highly interrelated (cf. Liu & Lesniak, 2006; Löfgren & Helldén, 2009; Stevens et al., 2010). Our findings revealed that although students' understanding of matter can be described by a "skeleton" model, there is a unique sequence of how students progress in their understanding for each of the four aspects (see previous section). In addition, our findings provide evidence, that the development of understanding in relation to the four aspects of matter is highly intertwined. That is, students' understanding of the structure and composition of matter or chemical properties and change highly interferes with their understanding about conservation of matter or its physical properties and changes.

As the body of research used for this review was limited by given criteria (see method section) a few studies could not contribute to the findings (e.g. Ayas et al., 2010; Smith, Wiser, Anderson, & Krajcik, 2006; Treagust et al., 2010). Although the way the authors describe students' progress in understanding slightly differs from our findings, these studies support the view that students' understanding holds some levels related to different aspects of matter and that students progress in their understanding by being more and more able to make connections between these aspects. In order to provide more evidence about the nature of these levels, an empirical validation of the model is needed in order to refine or revise the levels of understanding in respective.

It is not suggested by the authors to solely use the model presented in this study when it is to investigate of students' understanding of matter. In contrary, focusing on particular points of schooling this model may be too coarse-grained in order to describe students' progression within one single grade or within one teaching unit. On the one hand, students' understanding described in this model goes beyond what is appropriate to (for example) K-8 students, on the other hand, there are other pieces of scholarship doing an excellent job in detailing this age's students understanding and possibilities to foster their understanding in respective (e.g. Smith et al., 2006).

Conclusion

In this systematic review of the research on students' conceptions of matter in the past decade a model was suggested that seems to be eligible to describe students' progression of understanding matter in respective four principle aspects. Starting from a naïve understanding of matter students are supposed to move along a sequence of levels of understanding towards a sound understanding of the submicroscopic structure of matter and its relation to macroscopic properties of matter. The model provided in this study tends to be a means to locate a student's understanding, detailing on what kind of understanding he or she can already build on and what are the next levels to reach in order to step forward towards a deeper, scientific understanding of matter. Moreover, connections to current projects which aim to elicit students' progression in understanding matter as well as limitations of the methodology used in this study have been discussed. Although on the one hand it can be considered "safe" to say that indeed students' understanding of matter was very well investigated during the past decades (cf. Talanquer, 2009), on the other hand this review reveals some important issues that need to considered for future research:

As students' understanding of matter is often described as inconsistent and dependent from the specific environment in which students' are supposed to show or proof their understanding - that is, the type of task, it's content and context – students' development of understanding is not supposed to be linear and might not be the same for every student (cf. Gómez et al., 2006; Nakhleh et al., 2005; Steedle & Shavelson, 2009). Therefore, one question is how can students be aligned to levels of understanding using - in contrast to the majority of studies – a more general or coarse-grained model like the one provided in this study. Closely connected to this issue is the development of proper assessment tools that allow researchers and teachers a valid interpretation of a student's test scores prior to this model as background. Once having elicit the facets of understanding that may hinder a student to progress in his or her understanding instructional components need to be provided that are research-proven to improve students' understanding.

However, although being deeply connected to previous research, this model needs to be empirically validated before next steps can be taken into account. First, it needs to be proven if the four principle aspects of matter can be seen as separated by empirical evidence. That is, although research suggest that an understanding of the four aspects is highly intertwined, there might be differences in how students' progress in their understanding within each of the four principle aspects. Second, evidence is needed that students' level of understanding indeed built a hierarchically ordered system and that adjacent levels can be distinguished from another. Third, it needs to be empirically investigated to what extent this model is indeed suitable to describe students' progress. These upcoming findings can be used for further refinement of the model in order to work towards a more fine-grained description of how students progress in understanding the concept of matter.

We feel that the benefit of the model presented in this study is two-folded. On the one hand, this model provides a frame to describe and structure both: research on students' understanding of matter and students' understanding of matter as such. On the other hand it might be used – again like Andersson (1990) did with his – to stimulate research at least in terms of providing researchers with information about which study covers which parts of the model and references that might be useful for their own research. As research suggests that validating a complex model like the one presented in this study is an extensive and iterative process of refining both: the underlying model and the utilized assessment instruments (c.f. Jin, Zhan, & Anderson, 2013; Merritt, 2010; Merritt & Krajcik, 2013; Stevens et al., 2010), the model presented in this study might be considered a sound starting point for current and future research on fostering students' progression in understanding matter.

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