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A tale of two progressions: students' learning progression of the particle nature of matter and teachers' perception on the progression

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Abstract

Learning progressions (LPs) provide researchers with a robust framework to describe the process of students' cognitive development in science and provide teachers with an effective reference to help students' competences develop. In physics education, the understanding of the particle nature of matter (PNM) is important, as it affects students' conceptualization of matter and, over the long term, the entire view of science. Developing a systematic understanding of the PNM requires an effective instruction. Teachers' instruction is heavily influenced by their understanding on students' progression. Therefore, this study first tested and refined students' LPs of PNM. Then, with the lens of LPs, we investigated teachers' perception on the progression. The results show that students' LPs of PNM in teachers' minds are partly different from students' actual situations, as most teachers have not been sufficiently informed of students' conceptual understanding of PNM and especially lack the knowledge of students' understanding in PNM at the lower level. When designing instruction, some teachers did not have an awareness of LP-based instructional design and sometimes neglected students' conceptual development. This study ends with some suggestions for supporting teachers' professional development.

Keywords Learning progression, Middle school physics, Particle nature of matter

Introduction

Promoting the development of students' core competences is the major concern of today's education reform, which has received widespread attention (e.g., European Commission, 2012; Ministry of Education [MOE], P. R. China, 2014; OECD, 2005). Learning progressions (LPs) are "descriptions of the successively more sophisticated ways of thinking about a topic", which are "crucially dependent on instructional practices" (National Research Council [NRC], 2007, p.214). Because of its value in coherently informing the design of standards, curricula, instructions, and assessments, a growing number of researchers believe that LPs have great potential to be an effective tool for promoting the development of students' core competences (e.g., Duschl et al., 2011; Jin et al., 2019; Krajcik, 2012; Yao & Guo, 2014, 2018). To date, focusing on core concepts and key practices in science, LP studies have evolved from proposing the initial hypothesis of possible levels (most were based on a systematic literature review) to investigating and describing students' actual learning progressions (most were based on cross-sectional or longitudinal assessments). Some countries, organizations, and researchers have used LPs to support curriculum design and assessment development (e.g., MOE, 2017; NGSS Lead States, 2013; NRC, 2012).

In addition, teachers' understanding and usage of LPs has become another key point of LP research (Jin et al., 2019). Since only a small number of teachers

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have opportunities to participate as researchers in LP research, the vast majority of teachers might lack an in-depth understanding of LPs. Therefore, when applying LPs to instruction (for example, applying LPs to improving instructional design or developing formative assessments), teachers may encounter many difficulties and challenges (Jin et al., 2015; Shavelson & Kurpius, 2012), such as in interpreting students' response with the learning progression, in making instructional decisions using students' ideas (Duncan & Hmelo-Silver, 2009; Furtak et al., 2014; Heritage et al., 2009). This situation will hinder LPs from fulfilling their potential to coherently improve science curricula, instructions, and assessments. Currently, there is an urgent call for research establishing a connection between learning progression and teachers' professional development (e.g., Alonzo & Elby, 2019; Gunckel et al., 2018; Krajcik, 2012).

Matter is a big idea in science that plays a key role in students' understanding of the nature and artificial world (Harlen, 2010; MOE, 2011; NGSS Leading States, 2013). The particle nature of matter (PNM), which is the core content affecting students' conceptualization of matter, is the key to developing a deep understanding of science (Feynman, 1995; Tsaparlis & Sevian, 2013). However, many studies have shown that students have difficulties understanding PNM, and many instruction methods fail to support students' conceptual development (e.g., Brook et al., 1984; Johnson, 1998; Taber, 1996). How teachers understand students' LPs of PNM, which is part of their pedagogical content knowledge (PCK), can influence their instructional design. Therefore, our research was composed of two successive sections. Section 1 tested and refined students' LPs of PNM. With the lens of LPs, section 2 investigated teachers' perception on students' progression.

Literature review

Learning progressions of matter

Almost all countries emphasize matter as one of the disciplinary core ideas of K-12 science curricula (e.g., MOE, 2011; NGSS Lead States, 2013). Numerous studies have found that students have a large number of misconceptions when understanding matter (e.g., Liu, 2001; Novick & Nussbaum, 1978; Renström et al., 1990; Tsaparlis &Sevian, 2013), especially understanding the PNM (e.g., de Vos & Verdonk, 1996; Treagust et al., 2010). In addition to examining the misconceptions in understanding PNM, researchers have proposed initial frameworks (Table 1) for the conceptual development of PNM in cross-age studies (e.g., Johnson, 1998; Liu, 2001; Renström et al., 1990). Although different researchers have different perceptions of the possible stages in the development of students' particle views, there is a consensus that students had a transition from having no particle views, to recognizing particles and particle systems, and then to understanding the relationship between particles, particle systems, and macroscopic properties of matter.

After the idea of learning progression was formally introduced in science education, researchers began to develop learning progressions of PNM. For the purpose of assessment and designing instruction, researchers have developed description of performance expectations of students' learning progression of PNM. A number of studies support the idea that students' understanding of matter develops from the macro to the micro, with some studies suggesting that students up to grade 6 understand matter from a macro perspective (e.g., Merritt & Krajcik, 2013; Smith et al., 2006). Over time, students' understanding becomes more complex and integrated. They can explain the macroscopic in terms of the microscopic and to acquire a systematic concept of particles (e.g., Hadenfeldt et al., 2014; Merritt & Krajcik, 2013).

Although there are differences in the specific description of some performance expectations, most studies agree that students' progressions of PNM generally start from recognizing macroscopic objects to understanding its microscopic nature; from knowing PNM fragmentarily to establishing an integrated understanding of the relationship between macro concepts and micro concepts

Table 1 Conceptual development of PNM

Research	Progressions of PNM
Renström et al. (1990)	(1) Matter as a homogeneous substance; (2) Matter as substance units; (3) Matter as a substance unit with "small atoms"; (4) Matter as aggregates of particles; (5) Matter as particle units; (6) Matter as systems of particles
Johnson (1998)	(1) Continuous substance; (2) Particles in the continuous substance; (3) Particles are the substance, but with macroscopic character; (4) Particles are the substance, and properties of a state are collective
Liu (2001)	(1) Students perceive matter to be something unnatural; (2) Students consider matter to include solids that demonstrate natural phenomena; (3) Students may perceive matter to be something unnatural that displays physical properties; (4) Students see matter as comprised of particles having natural characteristics; (5) Students might regard matter as particles that demonstrate natural phenomena; (6) Students may recognize matter as being comprised of particles that demonstrate physical properties or as something occupying different states that demonstrate chemical properties; (7) Students appreciate that matter comprises particles responsible for chemical reactions

(e.g., Hadenfeldt et al., 2016; Liu & Lesniak, 2006; Merritt & Krajcik, 2013; Smith et al., 2006, for a review, see Hadenfeldt et al., 2014).

The hypothetical framework of this study synthesized the K-9 part of previous studies on LPs of PNM (e.g., Hadenfeldt et al., 2016; Merritt & Krajcik, 2013; Smith et al., 2006), primary school science standards (MOE, 2017), and junior middle school science standards (MOE, 2011) into a four-level framework. The four-level framework (Experience—Mapping—Relation—System) used complexity as the progress variable (Bernholt & Parchmann, 2011; Neumann et al., 2013; Guo, & Yao, 2016) to organize the descriptions of students' understanding of the PNM from the lower anchor (experience level) to the higher levels (Table 2). The *experience* level (Level 1) describes the daily experience/fragmented facts that students should have/know, most of which are related to macroscopic phenomena. At the *mapping* level (Level 2), students are expected to recognize properties of macroscopic objects by mapping scientific terms and experience/facts; to use them to explain macroscopic phenomena; and to realize parts of matter that are too small to be seen by the naked eye and to recognize the idea of particles from this. At the *relation* level (Level 3), students are expected to recognize that matter is made of particles and establish the relation between macroscopic matter and microscopic particles. At the *system* level (Level 4), students are expected to develop a preliminary systematic understanding of PNM.

Pedagogical content knowledge

PCK, which is specialized knowledge integrating teachers' understanding of disciplinary knowledge and pedagogical knowledge, encompasses teachers' decision-making on how to organize and present the instruction of a topic to learners with diverse interests and abilities (Shulman, 1986, 1987). Most of the early work on the conceptualization of PCK were modified and developed it based on Shulman's definition (e.g., Hashweh, 2005; Loughran et al., 2004). To situate PCK in a large picture of professional knowledge and skills, the Refined Consensus Model (RCM) of PCK was recently developed (Carlson et al., 2019), which was centred around the practice of science teaching and combined PCK components with the complex layers of experiences. A key feature of this model is the identification of three distinct realms of PCK—collective PCK, personal PCK, and enacted PCK.

The constitution of PCK is complex. To obtain a fuller picture of teachers' PCK, researchers usually focus on the following three aspects: what teachers know, teachers' classroom practices, and teachers' decision-making (Baxter & Lederman, 1999). Each of these three aspects requires different research approaches. For example, questionnaires and interviews are usually used to

Table 2 Hypothetical learning progressions of the PNM

Level	Description of the level	Merritt, and Krajcik (2013)	Smith, et al. (2006)	Hadenfeldt, et al. (2016)	Middle School Standards (2011)	Primary School Standards (2017)
Level 4 System	Students explain phenomena using PNM (e.g., recognizing the relation of temperature with the motion of particles). Students distinguish spacing and motion of particles in a particular state. Students know that the particles of all objects are in constant motion, including solids. Students recognize the interactions between particles	✓ ✓ ✓	✓ ✓ ✓ ✓	✓ ✓ ✓ ✓	✓ ✓ ✓ ✓	
Level 3 Relation	Students know that matter is made up of particles. Students know that there are voids between particles. Students begin to use particles to explain some of the physical phenomena. Students know that particles in liquids and gases are in motion	✓ ✓ ✓ ✓	✓ ✓ ✓	✓ ✓ ✓	✓	
Level 2 Mapping	Students recognize tha different types of mt have different properties Students use macroscopic ideas to explain phenomena. Students realize parts of mater are too small to be seen by the naked eye and recognize the idea of particles from this	✓ ✓ ✓	 ✓	 ✓ ✓	✓ ✓	✓ ✓
Level 1 Experience	Students describe objects exactly as they appear. Students describe the phenomena related to matter (e.g., changing shapes, breaking into smaller pieces)	✓		 ✓		✓ ✓

investigate what teachers know (e.g., Jin et al., 2015; McNeill, et al., 2016; Sorge et al., 2019). To understand teachers' classroom practice, classroom observation is often used (e.g., Alonzo, 2012; Park & Chen, 2012;). There are also many studies using a mixed-method approach to analyze teachers' PCK during their planning, implementation, and reflection phrases of instruction (e.g., McNeill & Knight, 2013; Park et al., 2011). Magnusson et al. (1999) conceptualized PCK for science teaching as consisting of five components, including "orientations toward science teaching" "knowledge and beliefs about science curriculum" "knowledge and beliefs about students' understanding of specific science topics" "knowledge and beliefs about assessment in science" "knowledge and beliefs about instructional strategies for teaching science". Studies of PCK tend to focus on one or more of five components (e.g., N. Boz & Y. Boz, 2008; Siegel & Wissehr, 2011; Park & Oliver, 2009). In science education, "knowledge about students' understanding" and "knowledge about instruction" are two important components of PCK, which reflect teachers' knowledge of how to translate content knowledge (CK) into comprehensible knowledge for students (Park & Oliver, 2008; van Driel et al., 2002; Yang & Guo, 2008). The next paragraphs show that the research on learning progressions provides a new lens for studies on these two PCK components.

Pedagogical content knowledge and learning progressions

In recent years, researchers have studied the progressions of PCK (Schneider & Plasman, 2011) or conducted PCK-related research based on students' learning progressions (e.g., Furtak et al., 2012; Gunckel et al., 2018; Jin et al., 2015). For example, based on the 5 components of PCK and empirical research results on teachers' teaching performance in 5 different professional development stages, Schneider and Plasman (2011) described teachers' progressions on each component. Other examples can be found in research on teachers' LP-supported design of formative assessments (Furtak et al., 2014) or the design of an LP-based measurement for teachers' PCK (Jin et al., 2015).

In those studies, based on teachers' different understandings of students' LPs, researchers developed an analytical framework with which can distinguish different levels of professional development. These analytical frameworks provide new perspectives on the study of PCK. LPs can help researchers gain a deeper understanding of what teachers know about students, which is an important component of PCK and how teachers' knowledge progresses with the accumulation of teaching experience. In addition, LPs can help teachers improve their curriculum design and assessment design (e.g., Furtak et al., 2012; Gunckel et al., 2018). Meanwhile, the combination of PCK and LP provides new perspectives on LP research (Alonzo et al., 2019). However, compared to research on students' LP, there are few relevant studies on teachers (Jin et al., 2019). There is an urgent call for in-depth research on how teachers comprehend and use LPs for decision-making on instruction (Yao et al., 2023).

Method

In our research, we explore the relationships among students' LPs of the PNM and teachers' perceptions of their students' LPs of the PNM. Unlike studies on the general characteristics of PCK, we need to analyze teachers' perceptions within the specific context of students' LP of certain disciplinary core ideas to determine whether teachers' perceptions include the knowledge of students' LPs and whether teachers' perceptions match the actual progression states of students. We proposed two research questions: (1) How do middle school students progress in the LPs of the PNM? (2) How do middle school physics teachers view and understand their students' LPs of PNM?

To address the above questions, we have conducted the study in two sections. Section 1 have adopted an assessment-based approach which has been used in most LP studies on matter (e.g., Hadenfeldt et al., 2016; Merritt & Krajcik, 2013), and which follows a data-driven research paradigm. In this approach, the development of LPs starts from a hypothetical framework. Then, scholars collected representative data from the assessment to revise or validate the progression levels (Fig. 1). Following this research paradigm, we conducted a cross-grade assessment to promote understanding of middle school students' LPs of PNM.

The actual progression states of sample middle school students, which found in section 1 can provide an empirical foundation for investigating and analyzing middle school teachers' views of LPs of PNM. Based on the results, section 2 used questionnaires and interviews to investigate teachers' perceptions of their students' LPs of the PNM, with a specific focus on how teachers perceive their students' LPs of PNM.

Instrument

For section 1, we conducted a paper-and-pencil test to validate the hypothesis and to describe the progression states of the sample students. The development of the test instrument was based on existing LP studies (e.g., Hadenfeldt et al., 2016; Smith et al., 2006), misconception studies (e.g., Treagust et al., 2013), and the national curriculum (Appendix 1). The item had been checked and selected through a pretest in our team's previous study. The final test instrument was composed of 20 items, including 13 multiple-choice items, 4 two-tier choice and answer items, and 3 open-ended items.

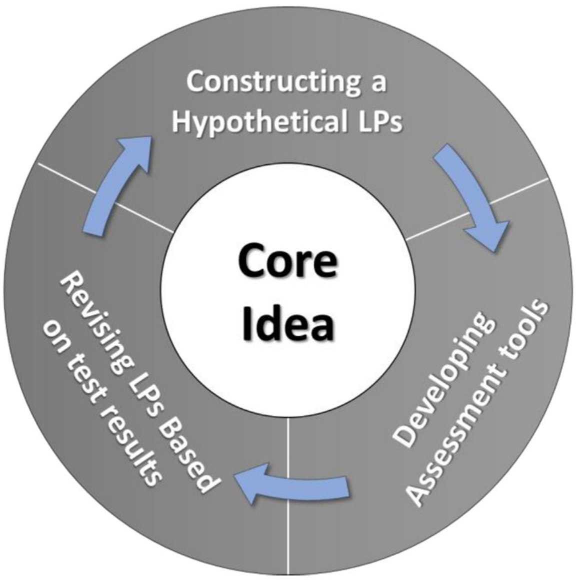

Fig. 1 The research circle in the assessment based approach for LP development

For section 2, we first developed a set of questionnaires on the teachers' perceptions of their students' LPs of the PNM. Because the information collected from the questionnaire was limited, we also conducted a semi-structured interview with teachers on the key points of the questionnaire. An outline of the interview is shown in Appendix 2.

The set of questionnaires is composed of two parts: (1) teachers' views of students' understanding of PNM and (2) teachers' knowledge for improving students' PNM understanding (Appendix 3). In the first part, there were 22 questions concerning teachers' views of students' PNM understanding. One sample item is shown in Table 3. Each question, which reflects a typical misconception or learning difficulty of students, corresponds to the typical performance of students at a certain LP level. To further address teachers' perceptions of the students' potential conceptual development during instruction, each question asks the teacher to estimate the proportion of students holding certain performance before and after instruction. In order to analyze the data quantitatively, we converted the proportion of students who had mastered the knowledge in the perception of teachers to 1–4 scores. To investigate what supports teachers' perceptions, we designed Q23 to ask "What is the information source supporting your judgment?" at the end of the first part of the questionnaire.

In the second part of the teachers' questionnaire, there were 6 questions about teachers' knowledge for improving students' PNM understanding. To investigate teachers' overall perception of PNM instruction, the first question in Part 2 investigated the potential sequence of their instructional design. Then, the following 5 questions in Part 2 investigate teachers' choice at some key points of PNM instruction, using some typical students' performances in section 1 as the question scenario (McNeill et al., 2016). Each of the above questions has two tiers: a multiple-choice question followed by an open-ended question that requires the teacher to explain their reason for choosing it.

Data source and analysis

In section 1, the test sample was administered to $N_1=452$ students in Grade 8 and Grade 9 (266 in Grade 8 and 186 in Grade 9) from middle schools in a large city of North China. $N_2=68$ middle school physics teachers voluntarily joined the survey of section 2. There were 60 valid samples after excluding questionnaires with unfinished choices/answer. Of the 60 teachers, 6 voluntarily engaged in our follow-up interview.

We used a partial-credit Rasch model (Winsteps version 3.72) and cluster analysis (SPSS version 23.0) to analyze the paper-and-pencil test and the first part of the questionnaire. For the quality of the items, it was mainly evaluated by the infit MNSQ, outfit MNSQ and ZSTD, and the ICC curve of the items. The Wright map presented in Fig. 2 indicated that the range of difficulty measure of items is able to cover the range of students' abilities. The second part of questionnaire was analyzed in terms of two aspects of "the instructional strategies used by the teacher" and "the reasons why they choose the instructional strategies", with the results classified according to the age of teaching. At the same time, for the interview section we used qualitative analysis classify and analyze the content.

We used Bookmark method to set performance levels of student learning progression (Cizek, 2001; Cizek et al., 2005; Cizek & Bunch, 2007). The process of Bookmark method normally has three rounds of Presentation-Discussion-Voting (PDV) (Fig. 3). First, we prepared reference materials, such as the ordered item booklet which presents items, coding rubric, and item difficulties estimated in the Rasch modeling, etc. Then we selected 9 experts in the field of physics education and divided them into 3 small groups. In each round of PDV, the experts need to decide where to place the bookmarks, based on the reference materials and their experience of which two groups of items have a significant difference in difficulty. The experts went through first two rounds of PDV in small groups. In the last round of PDV, the 9 experts among three small groups need to reach a general consensus about the performance levels of student learning progression. Finally, the experts completed a questionnaire to review the validity of the bookmark method.

Table 3 Sample item and coding of Part 1 in the teachers' questionnaire

	How many students have this idea/performance before instruction?					How many students have this idea/performance after instruction?				
	Unknown	**Less than 25%**	**25% To 50%**	**50% to 75%**	**More than 75%**	**Unknown**	**Less than 25%**	**25% To 50%**	**50% to 75%**	**More than 75%**
Q1 [a]. Students have no idea about particles and believe that matter is a continuous substance										
……										
Q16[b]. Students cannot use the idea of molecular dynamics to explain temperature-related macroscopic phenomena										
Coding [c]	/	4	3	2	1	/	4	3	2	1

[a] The typical performances of students in the items are all derived from and correspond with a certain level of the LPs of PNM in Study 1. For example, student performance on Q1 relates to the typical performance at Level 1 in the LPs of the PNM, while performance on Q16 is reflective of the typical performance at Level 3 in the LPs of the PNM

[b] The performance descriptions in our questionnaire are students' misconceptions or learning difficulties. Level 4 is the highest level in the LPs of PNM in Study 1, and students who reach Level 4 are expected to establish a systematic and scientific view of PNM and no longer have these misconceptions or learning difficulties. Therefore, items only correspond with Level 1 to Level 3 in the LPs of the PNM

[c] Since performance descriptions are all misconceptions or learning difficulties of students, if teachers believe that only a relatively small number of students (e.g., less than 25%) have a certain performance, this indicates that teachers believe that students with this performance have a lower PNM understanding than most students. For example, if the teacher believes that less than 25% of the students perform such that they "have no idea about particles and believe that matter is a continuous substance" (Q1), then the teacher believes that most of the students can recognize the idea of particles. This indicates that teachers believe that recognizing the idea of particles is not difficult for the students and that only the students with a lower level of understanding have this performance (i.e., having no idea about particles). Therefore, the coding and the proportion are reversed

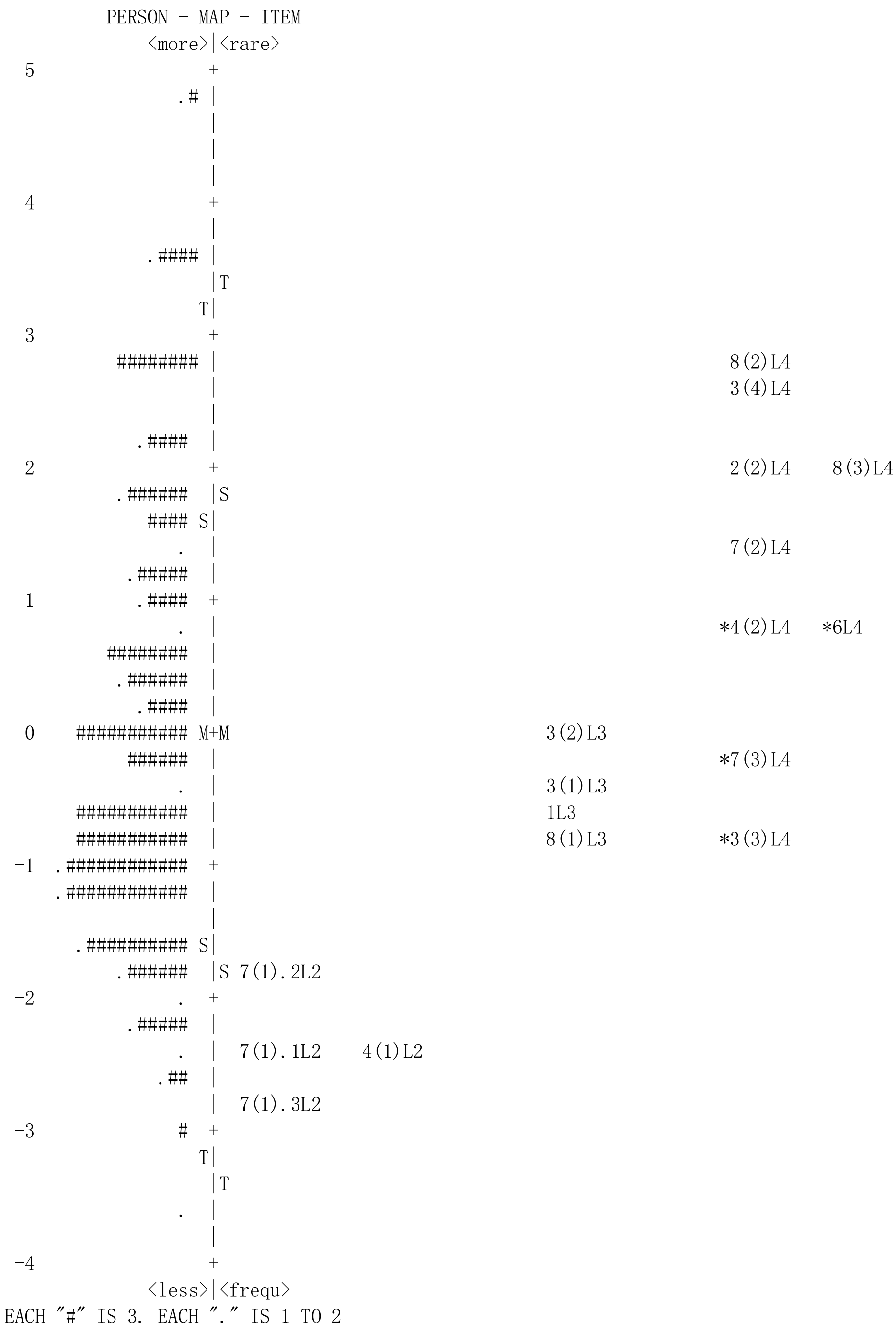

Fig. 2 The Wright map of paper and pencil test

Result

Students' LPs of PNM

First-round Rasch analysis on the entire dataset indicated that the test instrument had good reliability and validity (Bond et al., 2007): Sample reliability = 0.85, item reliability = 0.99, mean infit MNSQ = 0.98, 57.0% of the variance could be explained by the model, and the maximum portion not explained by the model was 4.3% (less than 1/10 of 57.0%). After eliminating 3 items that did not meet the standards of reliability and validity, we conducted the final-round Rasch analysis with 17 items. Data analysis indicated that the test instrument had good reliability and validity (Bond & Fox, 2007): Sample reliability = 0.85, item reliability = 0.99, mean infit MNSQ = 0.99, etc. The test instrument suited the sample: The average item difficulty (system default) was 0.00, while the students' ability

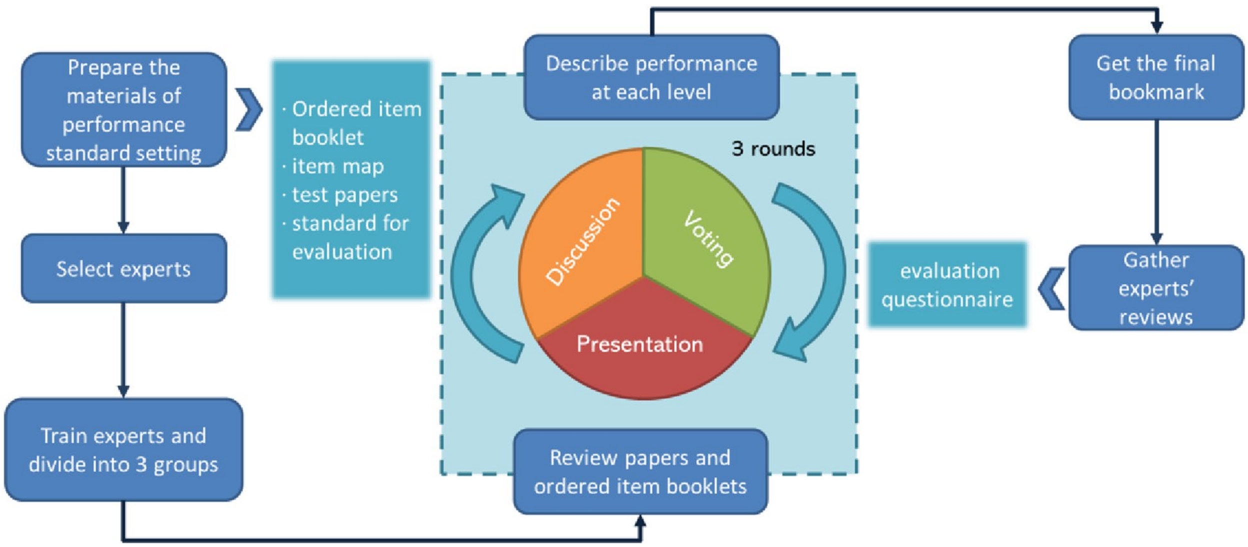

Fig. 3 The procedure of bookmarking method

was -0.01 in the same reference. Referring to the Bookmark Methods (Lewis et al., 1996), we delineated the range of ability values for each progression level (Table 4). Students' performance at each level met the hypothetical performance expectation (Table 2), which replicated previous research results on the LPs of PNM (Hadenfeldt et al., 2016; Merritt & Krajcik, 2013). Then, the distribution of the sample students was calculated. The results showed that most students were distributed in Level 2—Level 4 (Table 4). The largest number of students, 58.8% of the total sample, were at Level 3, the Relation level.

Then, we generated the Fig. 4 to present the distribution of students by grade (Fig. 4). Students in Grade 8 were mainly at Level 2-Mapping and Level 3-Relation. Students in Grade 9 were mainly at Level 3-Relation and Level 4-System. Compared to the 8th graders, there were significantly fewer 9th graders at Level 2 and significantly more at Level 4.

Teachers' perception on students' PNM understanding

We calculated Cronbach's alpha coefficient to test the reliability of the questionnaire. The Cronbach $\alpha = 0.901$ indicated that the questionnaire had good reliability.

Table 4 The distribution of the sample students at each level of the LP

Level	Range of ability value	Percentage	Sample mean ability value
Level 4	> 1.105	23.0%	2.34
Level 3	-1.535 —1.105	58.8%	-0.34
Level 2	-2.88 — -1.535	17.3%	-1.88
Level 1	< -2.88	0.9%	-3.13

Then we used a partial-credit Rasch model to calculate item-difficulty measurements on Questions 1–22 in the first part of the questionnaire (Table 5). Lower values for the difficulty measurement meant that the teachers believed most students could surpass this performance, i.e., only the students with a lower level of PNM understanding would have this performance. Then, a cluster analysis on teachers' answers to Questions 1–22 revealed that in the teachers' views, students' PNM understanding could be attributed to 3 levels: (1) the typical performance described in Q2, Q3, Q6, Q7, Q8, Q9, Q12, and Q17 could be grouped together, reflecting the lower level of PNM understanding; (2) the typical performance described in Q1, Q4, Q5, Q10, Q11, Q13, Q14, and Q15 could be grouped together, reflecting the middle level of PNM understanding; and (3) the typical performance described in Q16, Q18, Q19, Q20, Q21, and Q22 could be grouped together, reflecting the higher level of PNM understanding.

Comparing the levels that teachers expressed in section 2 and the empirical LP levels found in section 1 can help to understand the consistency or difference between the teacher's perceptions of students' LPs and the students' actual LPs (Table 6) and then help to investigate teachers' perceptions about students' PNM understanding. For example, the actual LP level corresponding to the performance "have no idea about particles and believe that matter is a continuous substance" (Q1) is the lowest level (Level 1). If the teacher believes that high-level students still perform as such, it means that the teacher's perception of student's LPs does not match the student's actual LPs, and the teacher may underestimate the student's ability. Table 6 shows that

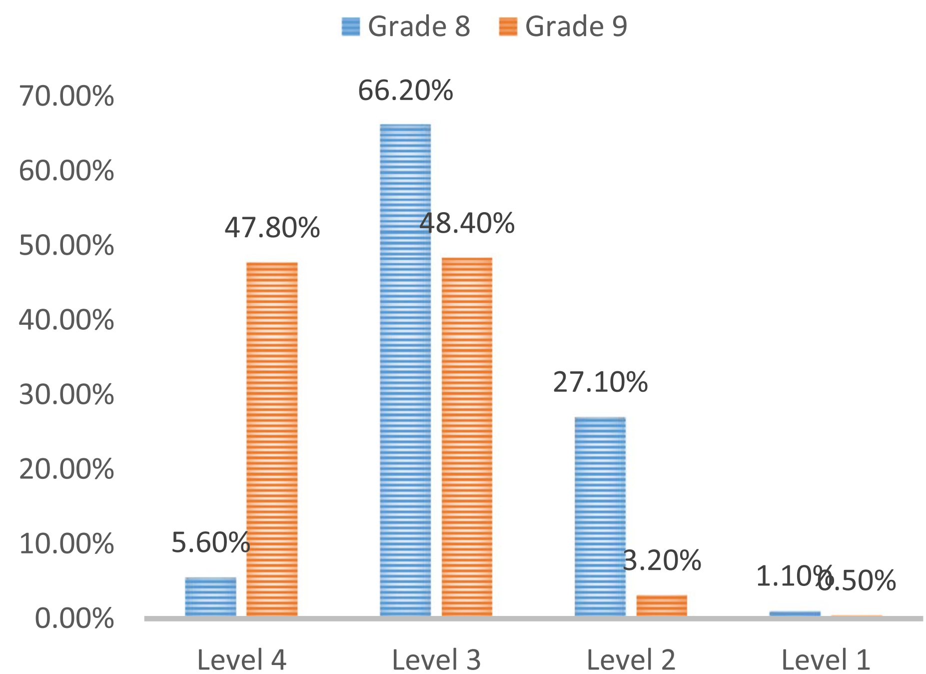

Fig. 4 The distribution of sample students by grade at each level

teachers' perception about students' PNM understanding partially matched the LPs of PNM. The teacher's perception about the upper level (level 3) matched the student's actual LPs (4/4). Regarding level 2, the teachers slightly underestimated the students at the upper level of LPs (2/16) and overestimated the students at the lower level of LPs (8/16). The teachers underestimated the students at level 1 (2/2). This indicates that teachers' perception at the upper level of LPs is more consistent with students' actual LPs of PNM, while their knowledge about students' lower-level performance is fragmented and insufficient. The results are corroborated by the findings from the interviews. In the interviews, every teacher (6/6) gave a confident description of the student performance expectation after instruction (Interview Question 1), but only half of the teachers (3/6) clearly described their student performance expectations before instruction (Interview Question 3). Additionally, teachers' knowledge of student post-instruction performance was more systematic than their knowledge of students' pre-instruction performance.

Table 5 The item difficulty as perceived by teachers

Item	Difficulty Measurement	Item	Difficulty Measurement
1	-0.15	**12**	-0.77
2	-0.46	**13**	0.14
3	-0.53	**14**	0.09
4	0.11	**15**	-0.11
5	0.09	**16**	0.63
6	-0.4	**17**	-0.29
7	-0.91	**18**	0.42
8	-0.34	**19**	0.73
9	-0.59	**20**	1.04
10	-0.13	**21**	0.68
11	-0.1	**22**	0.86

The sources of teachers' perceptions on students' PNM understanding

Analysis of the last question in the first part of the questionnaire showed that (1) 16.7% of the teachers made their judgment merely by guess; (2) 83.3% of the teachers made judgments based on their personal experience; and (3) none of these teachers referenced any literature (Table 7). The younger teachers (with 1–10 years of teaching experience) made the most guesses. The teachers with 11–20 years of teaching experience behaved better than their younger and elder colleagues (who made fewer guesses). The result that 1/6 teachers did not pay attention to students' performance and no teacher read teaching-support literature during their everyday teaching comes as a shock to the researchers. The above findings were generally consistent with the interview results. All interviewed teachers (6/6) derived

Table 6 Comparison of the LP levels in teachers' perceptions with students' actual LPs

Student performance corresponding to the question	Actual LP level	The level in the teachers' views
Students believe that particles in solids, liquids, and gases are all scattered	3	3
Students are not aware of the collisions that exist between particles	3	3
Students cannot determine the difference in the interaction forces between particles of solids, liquids and gases based on differences in the voids between the particles	3	3
Students are unable to explain the effects of temperature on macroscopic phenomena in the context of energy and molecular dynamics	3	3
Students believe that the gap between particles can be reduced to 0 and the particles can be pressed tightly together	2	3
Students do not know that there are gravitational and repulsive forces between particles	2	3
The student believes that the particle is moving under the force of other objects	2	2
Students believe that there are no gaps between the particles of an object and that they are close together	2	2
Students cannot simply explain the phenomenon of diffusion from the angle of particles	2	2
Students believe that the particles inside a stationary object do not move	2	2
Students do not know that the higher the temperature, the faster the thermal motion of the molecules	2	2
Students think that particles move only when they are heated	2	2
Students believe that the voids between solid particles, between liquid particles, and between gas particles are the same	2	1
Students believe that the gas particles float in the upper part of the closed container	2	1
Students believe that the change in volume of the same object is due to the change in volume of the particles within the object	2	1
Students believe that matter visible to the naked eye is made up of particles	2	1
Students believe that there are substances other than particles in matter	2	1
Students think that the gas particles sink in the lower part of the closed container	2	1
Students think that the particles move spontaneously in a certain direction	2	1
Students believe that the change in volume of the same object is due to a change in the number of particles within the object	2	1
Students do not understand the size of particles and cannot compare the size of particles and matter	1	2
Students have no idea about particles and believe that matter is a continuous substance	1	2

their knowledge about student performance primarily from their own experience, accumulated through daily questioning, practice, and testing of students. Taking Teacher F's response as an example:

> *We have taught long enough to get a sense of at what level students have knowledge. You can do the same by keeping an eye on their daily practice and answers on the test. I have never done a pretest yet, but I think it is interesting to try it in the future (Teacher F).*

Teachers' instructional decision

Teachers' responses to the second part of the questionnaire provide a lens through which to inquire about teachers' instructional decisions. The first question of this part is about the sequence of their instructional design for PNM. Almost all teachers (98.3%) would like to start from "matter is made of particles", and more than half of the teachers (68.4%) put the "interaction between particles" at the end, although they had multiple teaching sequences of "matter is made of particles"

Table 7 The statistics on the basis of teachers' judgments (grouped by teaching experience)

Judgment basis	All teachers	Responses by groups of teachers		
		1–10 years of teaching experience	11–20 years of teaching experience	21 + years of teaching experience
A. Guess	16.7%	29.2%	6.7%	16.7%
B. Literature	0.0%	0.0%	0.0%	0.0%
C. Teaching experience	83.3%	70.8%	93.3%	83.3%
D. Others	0.0%	0.0%	0.0%	0.0%

Table 8 The statistics on the basis of teachers' judgments (grouped by teaching experience)

Judgment basis	All teachers	Responses by groups of teachers		
		1–10 years of teaching experience	11–20 years of teaching experience	21 + years of teaching experience
MMP-MG-MTM-IM	36.7%	47.4%	36.4%	25.0%
MMP-MG-IM-MTM	15.0%	31.6%	9.1%	5.0%
MMP-MTM-MG-IM	30.0%	21.0%	31.8%	35.0%
MMP-MTM-IM-MG	8.3%	0.0%	13.6%	10.0%
MMP-IM-MG-MTM	8.3%	0.0%	9.1%	15.0%
MTM-MMP-MG-IM	1.7%	0.0%	0.0%	5.0%

(MMP), "molecules have gaps between them" (MG), "molecular thermal motion" (MTM) and "interaction between molecules" (IM). The sequence choice is in line with the LPs of PNM in general. Meanwhile, a detailed analysis of the teaching sequences of teachers with different teaching ages shows that teachers' sequence choices are more diversified as their teaching ages increase (Table 8).

Each question in the second part of the teacher's questionnaires also pursues the reasons for the teacher's choices. Regarding the reasons for the choice in Question 1 (teaching sequence), approximately half of the teachers (53%) chose option C, whose main consideration was whether it fit the sequence in which students build their PNM understanding. 33% of the teachers chose option B, whose main consideration was whether it fit into the order of research development of PNM in science. 14% of the teachers chose option A, which does not consider either the developmental process of students' understanding or the logic of scientific knowledge itself and is simply taught in the sequence recommended by the textbook.

Questions 2–6 investigated the choice of teaching methods at some key points of PNM instruction. The results show that on each question, most teachers (mean proportion = 90.6%) tend to help students advance to higher levels of PNM understanding with directly observable examples that can be seen by the naked eye of students or use multimedia means such as video demonstrations and photographic displays of electron microscopes to help students transform their original misconceptions and build a scientific understanding of the PNM. Only a few teachers (mean proportion = 9.4%) chose to use the direct-lecture approach. When teachers were grouped according to their teaching experience, there was little difference in the practices used by each group.

The analysis of the reasons for selection is carried out in conjunction with the interview. On each question, approximately half of the teachers made their instructional choice in consideration of students' ideas. In these responses, teachers were able to explain the reasons for choice in relation to the students' learning situations as described in Questions 2–6, although they were not yet linked to LPs of PNM. For example, in answers to Question 2, 58.3% of teachers' explanations were linked with the students' learning situations:

> *It is necessary to consider whether the understanding from macroscopic phenomena to microscopic nature can be achieved. Abstract microscopic problems are difficult for middle school students to understand. It would be easier to understand if they can make analogies based on macro phenomena (Teacher No. 6) or "Experimental phenomena and photographs of things need to be used to supplement students' experiences as a cognitive base. This can help them understand the gaps between particles." (Teacher No. 32)*

Alternatively, more than 40% of the teachers did not explain their choice from the perspective of students but more from the perspective of teaching convenience. For example, in Question 2, Teacher 37 wrote that "Displaying pictures can be viewed as object-based teaching: easy to use and easy for being in control of time". In sum, the responses in Part 2 of the questionnaire and interviews further complemented previous results. A few teachers lacked attention to students' learning states. Many teachers had a sense of design instruction according to students' learning states. However, teachers had a more systematic and comprehensive perception on what students knew after teaching than they did before teaching. Therefore, their perceptions of students' LPs of PNM can only support part of their instructional design.

Discussion

This study contains two sections, one on students' LPs and one on teachers' perceptions of students' progression. In the first section, 452 middle school students participated in an assessment measuring their PNM understanding. The assessment results indicated that the performance of the sample middle school students from China generally matched the LPs for PNM developed by previous research in Germany and the USA (e.g., Hadenfeldt et al., 2016; Merritt & Krajcik, 2013). Most of the sample students were able to establish a basic understanding of the PNM. Similar to the previous research in the USA (Merritt & Krajcik, 2013), after instruction, almost half of the students reached Level 4. It is no coincidence that the main difficulty in their progression was to systematically establish the connections between micro mechanisms and macro phenomena. Students in all countries have limited understanding of these particle theory concepts (Treagust et al., 2010). Comparing the results of learning progression studies for core scientific ideas such as matter (e.g., Hadenfeldt et al., 2016; Merritt & Krajcik, 2013, as well as this study) and energy (e.g., Herrmann-Abell & Deboer, 2018; Neumann et al., 2013; Yao et al., 2017) in the United States, Germany, and China confirms that there are no significant cross-cultural differences in the LPs of core scientific ideas. LP-based assessment and learning analysis have the potential to provide a robust framework for more systematic international comparisons of science education and assessment of educational progress.

In the second section, we used questionnaires and interviews to investigate 60 middle school physics teachers' PCK, with a special focus on teachers' perceptions of student progressions, based on the LP results of PNM in section 1. The results obtained from the questionnaire and the interviews corroborate each other. The sample teachers' perceptions on students' progressions were inadequately comprehensive and differed from the actual situation of students. In particular, the teachers lacked a clear perception on3 student understanding at lower levels. They also had a very limited source of knowledge about student understanding of PNM. In particular, the teachers are similar as teachers in previous studies who had a superficial perception on students' understanding (e.g. Gunckel et al., 2018; Jin et al., 2015). Although most of the sample teachers were able to choose a suitable point at which to begin instruction and help students gradually build up their understanding of PNM with several teaching strategies, only some of the sample teachers actually considered students' understanding when designing their instruction. These teachers were aware of the need to set goals for their students and the necessity to gradually promote their students' development of understanding. However, they did not know how to design and adjust their teaching according to the progression of students' understanding to achieve the teaching objectives more efficiently. In contrast, they could only follow the design of the available teaching resources (at most times, the textbook) to carry out teaching. In this situation, a lack of autonomy and flexibility in teaching becomes an inevitable result. This is corroborated by the findings of studies (e.g., Furtak et al., 2014; Gunckel et al., 2018) on teachers' perception and application of LPs: Teachers are not sufficiently skilled in diagnosing and analyzing students' domain-specific cognitions, and they need the help of LPs in facilitating students' progressions. In addition, the younger teachers (with 1–10 years of teaching experience) made the most guesses for judging their students' PNM understanding. This suggests that they do need more support. It is necessary to provide preservice teachers and young teachers with learning progressions as support materials for professional development (Aufschnaiter & Alonzo, 2018).

Conclusion

Compared to students from other countries, there are no significant cross-cultural differences in the LPs of PNM. However, there is a gap between teachers' perceptions of students' progression and the actual situation of students. Teachers lack a clear perception of student understanding especially at lower level, and they have limited source of knowledge about student understanding of PNM. As a result, they cannot design and adjust instruction efficiently according to the progression of students' understanding.

Both science-education researchers and policy-makers agree that LPs have great potential to bring coherence to science curricula, instruction, and assessment. Currently, transferring LPs from researchers to teachers is a key part of realizing the potential. The premise of this view is that teachers do need LPs and are willing to accept them. Regarding the first premise, at least in China, where LPs are not as popular among teachers or policy-makers as in the USA, some teachers still would like to contest the following question: "Do we truly need the LPs?" After all, before the teachers are exposed to the LPs, they believed that they had already become close to their students or at least had spent more time together than science education researchers have. Moreover, some teachers might argue that they already have many teaching resources: curriculum standards, textbooks, and assessment-support materials. Our study provides empirical evidence to respond to this question. Similar to the misconception studies that provide legitimacy and research bases for conceptual change research (Vosniadou, 2013), the discrepancy between teachers' perceptions of students' progression and students' actual situations, which are revealed in this study, provides support for the legitimacy of enhancing teachers' attention to students' LPs.

As mentioned above, LPs should be used by teachers to achieve positive learning outcomes. Therefore, we need to fill the gap between teachers' perceptions of students' progressions and students' real LPs, by facilitating teachers learn and understand about the underlying theoretical ideas of LPs, as well as use LPs and LP-based systems. Further improving teachers' understanding of student thinking requires a more comprehensive support system, namely, to provide teachers with a toolkit or suite (Redish, 2003) that is solidly grounded in LP research. Within this toolkit, an educative curriculum (Davis & Krajcik, 2005), assessment tools (especially formative assessment tools, see Furtak et al., 2012), and teacher training program (Aufschnaiter & Alonzo, 2018; Jin, et al., 2015) are all essential (Jin, et al., 2019; Krajcik, 2011; Lehrer & Schauble, 2015). For the development of teacher-training programs, making teachers aware that their understanding of students is not yet systematic is an important first step in teacher training, which is similar to exposing students' preconceptions in conceptual change research. In sum, people are telling a tale of two progressions: students' LPs and teachers' progression of PCK (Schneider & Plasman, 2011). Among the many studies that have contributed to filling the gap between the two progressions (e.g., Aufschnaiter & Alonzo, 2018; Furtak et al., 2014; Gunckel et al., 2018; Jin, et al., 2015), our current study has only made a small first step in a series of research on the two progressions. Regarding the five components of the construct of PCK (Magnusson et al., 1999; Park & Oliver, 2008), the current study is limited to only two components (knowledge of students' understanding and knowledge of instructional strategies), and the research on knowledge of instructional strategies is not sufficient. In addition, the information we collected belongs to teachers' declarative PCK (with a comparison to the dynamic PCK, Alonzo et al., 2016). Our subsequent research should further expand the research tools and develop an integrated analysis system for the two progressions consisting of student assessment, teacher questionnaires, interviews, and classroom-observation frameworks. The data collected by this analysis system can be used for teacher training and curriculum development.

Abbreviation

LPs	Learning progressions
PNM	Particle nature of matter
PCK	Pedagogical content knowledge
RCM	Refined consensus model
PDV	Presentation-Discussion-Voting
MMP	Matter is made of particles
MG	Molecules have gaps between them
MTM	Molecular thermal motion
IM	Interaction between molecules

Supplementary Information

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Additional file 1: Appendix 1. Summary information table for test items.

Additional file 2: Appendix 2. Outline of the interview.

Additional file 3: Appendix 3. The questionnaires of teachers' PCK.

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Authors' contributions

YY, YJX, & GYY made contributions to the theoretical foundation and the design of the study. YY made contributions to the collection, YY, YJX made contributions to analysis and interpretation of data, as well as LYX, SXH made contributions to the writing and revision of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

We have ethical approval and participant consent.

Consent for publication

We have consent for publication.

Competing interests

The authors declare that they have no competing interests.

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