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Published Research On Pre-College Students' And Teachers' Nanoscale Science, Engineering, And Technology Learning

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Review

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Abstract: By the end of the first decade of the 21st century, it was clear that nanotechnology was emerging as one of the most promising and rapidly expanding fields of research and development worldwide. It would not be long before scientists, science educators, engineers, and policy makers began advocating for nanoscience, engineering, and technology (NSET) related concepts to be introduced in K-12 classrooms. Indeed, there has been a surge in the development of pre-college NSET-related education programs over the last decade, as well as millions in funding to support the creation of these programs. In an effort to characterize the state of research to date on pre-college students' and teachers' learning of NSET content knowledge and related practices, we have conducted a systematic review of the peer-reviewed, published research studies to answer the following questions: What NSET content knowledge and practices in a pre-college context have been examined in empirical learning studies? What do these studies tell us about the NSET content knowledge and practices that pre-college students and teachers are learning? Implications and recommendations for future research are also discussed.

Keywords: nanoscale science, engineering, and technology (NSET) education; pre-college student learning; pre-college teacher learning.

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1 Introduction

In the early years of the 21st century, as research and development in nanoscale science, engineering, and technology (NSET) was rapidly advancing, calls were proliferating for the integration of basic concepts and principles of the nanoscale into K-12 science, technology, engineering, and math (STEM) education (e.g., [1–4]). There existed urgency for the global STEM education community to develop and provide the learning experiences necessary for future generations to understand the principles that govern behavior of materials at the nanoscale. With an increased focus on infusing the nanoscale in pre-college classrooms combined with a wave of new sources of funding, it would not be long before STEM education fields, and science education in particular, witnessed a surge in the development of new pre-college NSET education programs and initiatives. Many of these programs and initiatives originated in the US, including (but not limited to) the following: NanoLeap, the Nanoscale Informal Science Education Network (NISE Net), NanoSense, NanoTeach, National Center for the Teaching and Learning in Nanoscale Science and Engineering (NCLT), National Nanotechnology Infrastructure Network (NNIN), and the Materials Research Science and Engineering Center (MRSEC) (see also [5, 6]). Globally, programs were being developed that are now long-standing, well-established initiatives including (but not limited to) Taiwan's K-12 Nanotechnology Program [3], the European Commission's NANOYOU [7], and TechNyou in Australia [8] among others. As a result of these initiatives, numerous pre-college courses, modules, and lessons for teachers' and students' learning of NSET have been developed, suggesting that NSET definitely is making its way into pre-college classrooms worldwide [5, 6, 9, 10].

2 The big ideas in nanoscale science and engineering

Concomitant with the onset of the development of NSET learning experiences, scientists and science educators recognized the urgent need to identify and articulate the NSET understandings that are important and appropriate for learning at the pre-college level and the corresponding learning goals that should be driving the design of instructional experiences in NSET. To begin this work, a group of scientists, science educators, and science teachers convened in a series of workshops jointly sponsored by the NCLT and Stanford Research Institute (SRI) International with the goal of developing a consensus about the "big ideas" of nanoscience and engineering (NSE) and corresponding learning goals that would be appropriate for grades 7–12 (for a description of the entire process, see [11], Appendix A). The term "big ideas" refers to far more than simply a set of discreet and disconnected facts. Big ideas are the central concepts and organizing principles of a discipline that have broad explanatory power. According to Stevens et al. [11], the big ideas "provide a framework for the long-term development of student understanding, allowing teachers and students to revisit ideas throughout the 7–12 curriculum and to build conceptual understanding during those years" (p. xii). The NCLT and SRI collaboration resulted in the identification of nine big ideas in NSE as significant and developmentally appropriate learning goals for grades 7–12 NSE instruction: size and scale; structure of matter; size-dependent properties; forces and interactions; quantum effects; self assembly; tools and instrumentation; models and simulations; and science, technology, and society. Stevens et al. acknowledged that one of the major challenges in developing a consensus of the big ideas for grades 7–12 instruction was that some of the NSE big ideas are related not only to nanoscience, nanoengineering, and nanotechnology but also to science more broadly – that is, the big ideas of NSE are also the big ideas of all of science. Nonetheless, it is important to articulate these big ideas in the context of NSE so that they may be integrated across disciplines [11]. In 2009, the *Big Ideas of Nanoscale Science and Engineering: A Guidebook for Secondary Teachers* was published by the National Science Teachers Association (NSTA) Press (NSTA is the largest organization of science teachers worldwide, with over 55,000 members [12]). To date, this remains the most comprehensive document available that identifies NSET concepts with corresponding learning goals and illustrative phenomena that are appropriate for grades 7–12 instruction. In this paper, we will use the *Big Ideas of Nanoscale Science and Engineering* as a framework to organize the findings of this study.

3 Purpose and scope

Despite the growth in the number of pre-college NSET-related education programs over the last decade as well as the millions in funding that have supported the creation of these programs, there does not exist a systematic analysis of empirical research that has been conducted on pre-college students' and teachers' *learning* of NSET content knowledge and related practices – i.e., what do pre-college students and teachers know about NSET and what are they learning in NSET-related programs? Consequently, we were interested in examining what pre-college students and teachers are learning about NSET and what evidence research is providing to help educators understand how students and teachers are making sense of concepts and phenomena at the nanoscale.

The major purpose of this study was to identify published empirical research studies that report pre-college student and teacher NSET learning data and analysis and to synthesize the findings to determine the current state of research on NSET learning. The overarching research questions guiding this study were as follows: What NSET content knowledge and practices in a pre-college context have been examined in empirical learning studies? What do these studies tell us about the NSET content knowledge and practices that pre-college students and teachers are learning?

4 Methods

Since we were interested in reviewing studies that provided learning data and findings, we limited this review to include those studies that have been published in peer-reviewed journals and report empirical data on pre-college student or teacher learning related to NSET and NSET education. Hence, we were interested in a distinct subset of publications about NSET education. We did not include grey literature in this review (i.e., conference proceedings, technical reports, and theses). Additionally, we did not include in this review articles that primarily report perceptions and attitudes or articles that focus on the evaluation of programs and pedagogies, as these foci are outside of the scope of this review. For studies reporting findings related to student learning, the data by and large addressed students' conceptual understandings of science content related to NSET. For studies reporting findings pertaining to teacher learning, data addressed not only teachers' content knowledge but also knowledge relevant to teaching specific pre-college NSET concepts or skills. Most of the studies reviewed took place in the context of an instructional intervention. However, we also included studies that examined NSET conceptions at a "snap-shot" in time, as these studies provide critical foundational information for designing future NSET learning materials as well as NSET-based learning environments.

The articles for this review were retrieved using several methods. First, we utilized the search function provided by STEM education-related journal websites. Search terms included the following key words as well as combinations of these keywords: nanoscience, nanotechnology, nanoengineering, nano, nanoscale, science, technology, engineering, education, secondary, K-12, and pre-college. We searched the following peer-reviewed research journals to retrieve articles: *Chemistry Education Research and Practice*, *International Journal of Engineering Education*, *International Journal of Science Education*, *Journal of Chemical Education*, *Journal of Engineering Education*, *Journal of Nano Education*, *Journal of Pre-College Engineering Education Research*, *Journal of Research in Science Teaching*, *Journal of Science Education and Technology*, *Journal of Science Teacher Education*, *Research in Science Education*, *Science Education*, and *Studies in Science Education*. Second, using the same search terms above, we used Google Scholar (scholar.google.com) to find articles that we did not retrieve from a search of peer-reviewed research journals. Additionally, we utilized the "Cited by" function on Google Scholar to find new articles for our review that cited articles we already had found. Finally, we conducted an exhaustive search by examining the lists of references of each of the articles reviewed, iteratively retrieving relevant articles until no new articles were found.

4.1 Characterization of articles for review

We found a total of 51 peer-reviewed journal articles on pre-college NSET education. Each member of the author team read each of the 51 articles. From our initial reading and discussion, we developed five categories for coding the central focus/purpose of each article: (1) empirical studies on pre-college student and/or teacher learning and cognition; (2) descriptions of pre-college programs, lessons, and/or activities that include an evaluative assessment of the learning materials/environment; (3) descriptions of pre-college programs, lessons, and/or activities only; (4) research reviews, position papers, and theoretical papers; and (5) other research focus (including assessment instrument development; studies on pre-college teachers' or students' perceptions, beliefs, and/or attitudes but not related to a specific program, lesson, or activity). Each of the author team members independently categorized each article and compared results. When one member was in disagreement, we discussed the article and came to a consensus. We found 26 empirical studies on pre-college student and teacher learning; eight descriptions of pre-college programs, lessons and/or activities that include an evaluative assessment of the learning materials/environment; four descriptions of pre-college programs, lessons, and/or activities; five research reviews, position papers, and theoretical papers; and eight other research articles. Figure 1 displays the distribution of articles by focus of article and year published.

4.2 Data analysis

We characterized each of the 26 articles that reported an empirical study of pre-college student and/or teacher learning and cognition according to the following components: study participants in terms of grade level, NSET content focus, research questions, pedagogical approach of intervention (when applicable), learning measures/data, and findings. We also were interested in the nature of the content learned, specifically whether the content involved conceptual understanding (definition) or was simply an assessment of factual knowledge and included this characterization within the narrative of the findings. We then synthesized findings across articles according to NSET content, organizing the findings using the *Big Ideas of Nanoscale Science and Engineering* [11] as an organizational framework (henceforth, "big ideas").

5 Findings

This section describes our findings organized in terms of the big ideas. We start with a description of each big idea along with a description of the intended learning goal or research goal, as appropriate. We also describe when

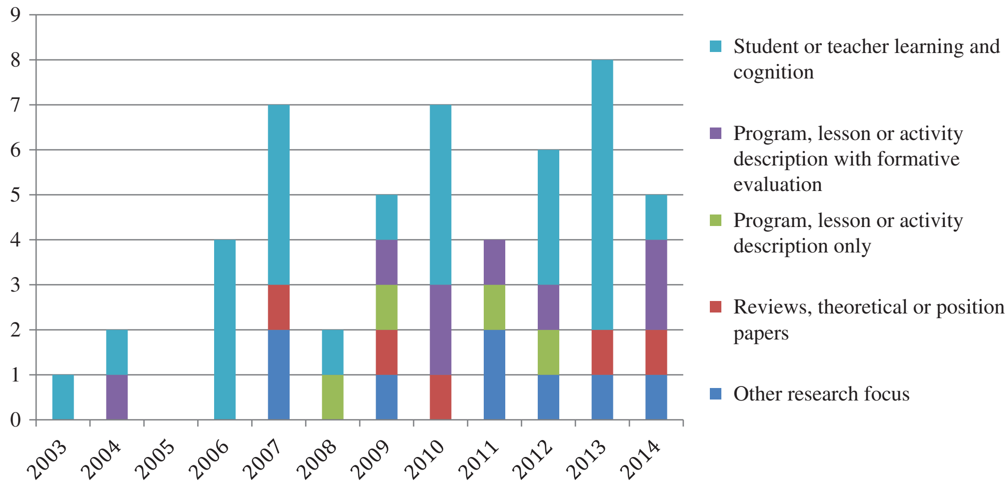

Figure 1 Pre-college NSET articles categorized by focus and year published.

applicable each of the curricular interventions provided as a treatment followed by a summary of the research findings. Table 1 summarizes the studies reviewed in this section.

5.1 Learning research on size and scale

The big idea that has received the greatest attention in NSET learning-related research is size and scale. Fifteen out of the 26 articles we reviewed examined size and scale, either as the main focus of the study or as one of several big ideas. Stevens et al. [11] refer to the construct of size as "the extent or bulk amount of something" (p. 5). Scale refers to the characterization of broad ranges of size into identifiable "worlds" (e.g., cosmic, micro, and nano), by unit of measurement, tools, or landmark objects [13]. Learning research in size and scale has particularly focused on individuals' different conceptualizations and how those conceptualizations vary with age, grade level, everyday experience, culture, and expertise in STEM disciplines.

5.1.1 Conceptualizations of size and scale

One way in which individuals make sense of the concept of size is to create distinct categories of spatial distances and objects perceived as being similar in size relative to conceptual landmarks (e.g., cosmic scale distances, room sizes, human sizes, and atomic scale), the most common landmark being the size of oneself [13, 14]. These researchers also have found that the number of categories conceptualized tends to increase with age, grade level, and experience. For example, among a sample of grades 5, 7, and 9 students, gifted seniors, and experts (doctoral students), Tretter et al. [13] found that students from elementary through ninth grade represented only one category (small) for objects smaller than themselves, while gifted seniors identified three categories (small, very small, and microscopic) and experts identified five categories (small, very small, barely visible, many atoms, and atomic). Thus, the younger the student, the fewer distinct conceptual categories they tended to identify. Likewise, Jones et al. [14] found that among experienced and novice (pre-service) teachers, novice teachers conceptualized only one category of size smaller than human scale compared to the experienced teacher group who reported five size categories smaller than human scale, with two categories below visible limits.

Findings from these studies of size and scale also noted techniques by which more advanced learners form and apply conceptualizations. For example, Tretter et al. [15] found that teacher experts and more advanced learners utilized the technique of unitizing, creating a new, more convenient, and personally meaningful unit for more abstract extremes of scale and working within that frame of reference (e.g., "light year" or "nuclear-size") (p. 1080), suggesting a learned ability to mentally transport oneself into other scale worlds spontaneously.

5.1.2 Relative and absolute size and scale rankings

Individuals tend to systematically misjudge the sizes of objects larger or smaller than themselves as bigger or

Table 1 Published empirical studies on pre-college student and teacher learning and cognition reviewed in this paper (alphabetically listed by first author).

References	Study participants/ learners	NSET content focus	Research questions or research goals	Pedagogical approach of intervention	Learning measures/ data	Synopsis of findings
Blonder (2010) [37]	14 high school science teachers.	Tools and instrumentation.	How did using an AFM model enhance teachers' knowledge regarding the AFM? How did using the AFM model influence teachers' attitudes toward using this model in their classes? Are teachers with different backgrounds in nanotechnology affected differently by the AFM teaching model?	Hands-on learning with manipulatives, demonstration experiment.	A personal meaning mapping technique; lab reports.	The teaching model (Lego-AFM) improved teacher's knowledge of AFM. The teaching model positively affected teachers' attitudes toward using the model in school and toward teaching nanochemistry.
Blonder and Sakhnini (2012) [20]	60 ninth grade students.	Size and scale, surface area to volume ratio.	To develop a nanotechnology teaching module that utilizes a variety of teaching techniques and supports students' understanding of two concepts: size and scale, and surface area to volume ratio.	Twelve weekly 45-min lessons and the creation and public presentation of a final project.	Pre- and post Nano Scraps activity in which students created a written representation of a nanoscale object, structured interviews, and final project presentation.	Providing students multiple opportunities to explore concepts in different contexts had a positive impact on student learning, particularly among the average and below average achieving students. Prior to the 12-week program, not one student could correctly provide an example of a nanoscale object. At the end of the series of lessons, 86% were able to do so. Additionally, all students chose multiple methods of expression of their chosen nanotechnology application in their final projects.
Bryan et al. (2012) [27]	7 middle schools and 17 high school science teachers.	Size-dependent properties, size and scale, tools and instrumentation, models and simulation.	Does science teachers' overall NSET content knowledge change as a result of their participation in a 2-week intensive content and pedagogy course? Does science teachers' overall NSET content knowledge change 8 months after the 2-week intensive content and pedagogy course has ended?	1-year professional development experience that included a 2-week intensive content and pedagogy course and academic year follow-up activities.	Pre-, post-, and delayed paper-and-pencil tests; teacher developed and implemented lesson plans.	Participants showed significant gains from pretest to posttest. A delayed posttest (8 months) showed significant gains compared to the pretest. On average, each teacher taught three of the 24 test items addressed in the professional development course. Twenty-three of the 24 test items were related to lessons taught by at least one teacher, and no more than six teachers reported teaching lessons related to any given item. Performance did not differ significantly on the delayed test on taught vs. non-taught items.

(Table 1: Continued)

References	Study participants/ learners	NSET content focus	Research questions or research goals	Pedagogical approach of intervention	Learning measures/ data	Synopsis of findings
Castellini et al. (2007) [16]	495 individuals, age 7 years through adult.	Size and scale, nanotechnology knowledge.	What is the public's "baseline" knowledge about nanotechnology, and nanometer and micrometer size objects?	N/A	Seven question survey.	Categories of identifiable "smallest things" consisted of small but visible things, atoms, microscopic objects, and sub-atomic particles, the accuracy of which increased with level of education. Respondents were more accurate in ordering the sizes of small but visible objects than small but invisible objects.
Daly and Bryan (2010) [42]	1 middle school and 18 high school science teachers.	Models and modeling.	What choices do teachers make for how to use models in their designed NSE instruction? What purposes do the models have? What reasons do teachers have for their choices?	1-year professional development experience that included a 2-week intensive content and pedagogy course and academic year follow-up activities.	Lesson plans for implemented model-based lessons; written responses to reflective practice protocol.	The study identified four ways in which teachers reported using models in practice: (1) tools for visualization and manipulation; (2) products of students' translation of ideas, knowledge, and data into a physical form; (3) representations for student comparison and critique as a measure of their developing understanding; and (4) means for investigation.
Delgado (2013) [18]	17 USC-native and 89 SI-native students in Mexico and 31 USC-native US students; middle school and high school.	Scale and measurement.	How do comparable SI-native and USC-native students differ in their knowledge of scale?	N/A	Paper and pencil assessment and an interview protocol.	SI-native orientation was found to have a positive impact on knowledge of scale and measurement. Factual knowledge-based tasks (those requiring factual knowledge from formal schooling) demonstrated no significant differences across SI- and USC-native students, with one exception being US students with higher mean college test scores who performed at a higher level. Some results suggest that schooling may help students build knowledge of scale and measurement.
Hale-Hanes (2014) [35]	120 high school students.	Self-assembly, entropy, and enthalpy.	To identify the effect of hands-on laboratory experiment vs. hands-on laboratory experiment with a computer simulation on students' understanding of entropy, enthalpy, and self-assembly.	A 60-min long hands-on laboratory experiment involving a model that can be manipulated and presents similar interactions as those seen in self-assembling systems on the nanoscale and the Molecular Workbench computer simulation.	Student self-assessment, a quiz with three open-ended questions, and a survey; a comparison/ analysis question.	Students who were exposed to both model-based activities expressed more in-depth understanding of entropy and intermolecular attractions and their role in self-assembly. Students' explanations of why small objects can spontaneously self-assemble into orderly structures.

(Table 1: Continued)

References	Study participants/ learners	NSET content focus	Research questions or research goals	Pedagogical approach of intervention	Learning measures/ data	Synopsis of findings
						were categorized. The students with the hands-on laboratory experiment provided repelling and polarity as a main explanation. The students with the computer simulation laboratory and hands-on laboratory experiment provided explanations that included a higher number of students selecting attraction and stickiness. In both cases, there were a large number of students who could not provide an explanation other than the difference in size of the objects.
Harmer and Columbia-Piervallo (2010) [38]	30 high-ability and 25 average-ability middle school students.	Tools and instrumentation; implementation of new technologies.	How does inquiry design affect students' knowledge of nanoscale science, nanotechnology, and electron microscopy? How does inquiry design affect student engagement with nanoscale science?	A 5-week course consisted of classroom sessions, reading, and a web-based science inquiry environment. Students were also provided remote access to a scanning electron microscope (SEM).	Pre- and post-questionnaires; daily student journals; interviews.	Significant gains for the high-ability group related to using nanoparticles to clean up pollution, matter at the nanoscale having different properties, and how images are created using the SEM. Significant gains for the average-ability group were seen in nanoparticle measurement, electron microscopy, size, and the application and control of new technologies. Affective gains were also observed with regard to career interest and technological and environmental responsibility.
Höst et al. (2013) [33]	5 high school students.	Size-dependent properties, forces and interactions, size and scale.	What are students' "baseline" conceptions about electric fields when applied to a molecular context, before any exposure to a virtual haptic model that renders the phenomenon? How does interacting with the multisensory visuohaptic model influence students' conceptual understanding of electric fields around molecules? How can the findings be used as an empirical basis for informing the development of educational virtual environments for learning about nanoscientific phenomena?	Multimedia learning (tactile feedback).	Student-generated diagrams; semi-structured interviews; think-aloud; computer analytics of user interaction.	Prior to exposure to a visuohaptic model, students' written responses displayed that they struggled to distinguish between the concept of polarity and electric field. The case-based interactive data indicated that tactile interaction may induce an active integration of electric field knowledge with molecular charge distribution. The multisensory visuohaptic experience of molecular properties promotes the fusion of physical and chemical concepts that are otherwise taught and treated as isolated pieces of knowledge.

(Table 1: Continued)

References	Study participants/ learners	NSET content focus	Research questions or research goals	Pedagogical approach of intervention	Learning measures/ data	Synopsis of findings
Jones et al. (2004) [23]	209 middle school and high school students.	Size and scale, tools and instrumentation.	How do haptic experiences influence students' concepts of viruses? Do haptic experiences with nano-sized objects change students' understandings of nanoscale? Are there differences in attitudes for those students who have a full haptic experience compared to students who receive a limited haptic experience?	Multimedia learning (tactile feedback).	Knowledge test; beliefs questionnaire; opinion questionnaire.	There were significant gains from pre- to post-instruction across treatment groups for knowledge and attitudes. Students in both treatment groups developed conceptual models of viruses that were more consistent with scientific research, moving from a two-dimensional to a three-dimensional morphology. There were significant changes in students' understandings of scale such as ability to identify examples of nano-sized objects and be able to describe the degree to which a human would have to be shrunk to reach the size of a virus. Attitudes of students who received full-haptic feedback were significantly more positive, suggesting that sensory feedback may have made the experience more engaging and motivating.
Jones et al. (2003) [36]	50 high school students.	Tools and instrumentation, size and scale.	How does the AFM-nM-based educational experience affect students' learning? How does the haptic feedback afforded by the AFM-nM experience influence students' conceptions of viruses?	Multimedia learning (tactile feedback), technology-mediated inquiry.	Paper-and-pencil knowledge test; opinion questionnaire; experience questionnaire; interview; design of a clay model; written (newspaper) stories.	Students' understandings of virus morphology and dimensionality changed as a result of the experience with the nM, the AFM, and the scientists. Students represented viruses on the pre-assessments as looking like those typically seen in textbook diagrams and depicted viruses as having two dimensions. After instruction, students depicted viruses as three-dimensional, increased their knowledge of microscale, and began to develop an understanding of the limitations of trying to visualize in three dimensions an object lying flat on a surface.

(Table 1: Continued)

References	Study participants/ learners	NSET content focus	Research questions or research goals	Pedagogical approach of intervention	Learning measures/ data	Synopsis of findings
Jones et al. (2006) [24]	36 middle school and high school students.	Tools and instrumentation, size and scale.	Are there differences by instructional treatments (PHANToM, haptic joystick, mouse) for students' knowledge of virus characteristics? Are there differences by instructional treatments (PHANToM, haptic joystick, mouse) for students' attitudes toward the instruction?	Multimedia learning (tactile feedback).	Paper-and-pencil test; survey; observations.	The addition of haptic feedback from the haptic-gaming joystick and the PHANToM provided a more immersive learning environment. It also made the instruction more engaging but may also influence the way in which the students construct their understandings about abstract science concepts.
Jones et al. (2013) [19]	26 veteran and 33 pre-service grades 7–12 teachers from Taiwan; 50 veteran and 51 pre-service grades 5–13 teachers from Austria; 50 pre-service middle school and high school teachers, and 16 veteran middle school, high school, college, and science center teachers from the US.	Size and scale.	Do teachers from Austria, Taiwan, and the US differ in their knowledge of spatial scale? Is knowledge of spatial scale related to the level of professional experience of teachers? Are there differences in teachers' reported in- and out-of-school experiences learning concepts of scale?	N/A	Scale Anchoring Objects (SAO); Scale of Objects Questionnaire (SOQ); Learning Scale Interview.	Accuracy of knowledge of scale, according to the SAO and SOQ, was not related to professional experience. There was a significant difference between teachers' concepts of scale by nationality. Austrian and Taiwanese participants were significantly more accurate than the US sample on the SAO and SOQ, with the Austrian participants scoring the highest. Interview data showed that the Taiwanese in-service teachers were more likely to report learning size and scale through in-school experiences than the other two cohorts. US participants most often reported learning size and scale from participation in hobbies and sports; Taiwanese through sports and reading, and Austrian participants through travel. Austrian teachers reported learning about scale through estimating, calculating, and converting scale, while US teachers described memorizing scales, and the Taiwanese teachers reported learning about scale relative to specific objects.

(Table 1: Continued)

References	Study participants/ learners	NSET content focus	Research questions or research goals	Pedagogical approach of intervention	Learning measures/ data	Synopsis of findings
Jones et al. (2007) [22]	78 high school and 66 middle school students (28 African-Americans, 109 European-Americans, and 5 Hispanics, 2 Asians).	Size and scale, tools and instrumentation.	Are there differences in students' attitudes (affective responses) toward nanoscale science instruction by ethnicity? Are there differences in students' perceptions of their engagement with nanoscale science instruction by ethnicity?	5 days of instruction as part of their regular science instruction that included a series of stations that included investigating viruses with a Nano-Manipulator; intro to the AFM, learning about scale, and watching "Powers of 10," interviews with scientists, and writing a newspaper article about their experiences.	Pre and post questionnaire about selected aspects of science analyzed for differences by ethnicity and grade level (middle or high school) with a Mann – Whitney U-test for ordinal data; qualitative analysis of newspaper stories coded also for differences in the stances taken by students of different ethnicities.	The results of the study showed that after instruction, African-American students were significantly more likely to agree with the statement that "science involves mostly memorizing things and getting the right answer," than European-American students. In addition, European-American students were significantly more likely to write their newspaper stories from a first person perspective than their African-American peers.
Jones et al. (2008) [14]	50 novice teachers (middle school and high school); and 16 veteran teachers (middle school, high school, university, science museum).	Size and scale.	How accurate are teachers' conceptualizations of spatial scale of objects and distances over many orders of magnitude? Do novice and experienced teachers' accuracy of scale concepts differ? What prior in-school and out-of-school experiences shaped experienced teachers' concepts of scale? What scale boundary distinctions do novice and experienced teachers hold?	N/A	Scale anchoring Objects (SAO); Scale of Objects Questionnaire (SOQ); Scale Card Sort task (SCS); Scale in the Curriculum Questionnaire (SCQ).	Both novice and experienced teachers were accurate at the human scale, but accuracy decreased for both groups the farther the scale was removed from the human realm. Both groups were more accurate when using metric, rather than body referenced measurements, and least accurate below the limits of visibility of the unaided eye. In contrast, the experienced teachers had a higher nanometer accuracy and a higher billion meter accuracy than the novice teachers. Thus, the experienced teacher group demonstrated more accurate conceptions at extremes of spatial scale. Results also showed that while both groups tended to overestimate the sizes of small objects and underestimate the sizes of large objects, the exaggerations of the novice teachers were more pronounced.

(Table 1: Continued)

References	Study participants/ learners	NSET content focus	Research questions or research goals	Pedagogical approach of intervention	Learning measures/ data	Synopsis of findings
Kumar (2007) [40]	109 prospective grades K-9 teachers.	Etymology of "nano", size and scale, quantum mechanics, technological applications of nano phenomena.	What general knowledge do undergraduate science education (K-9) students have about nanoscale science and technology?	N/A	Nano quiz consisting of ten multiple-choice items from the National Institute of Standards and Technology.	The average score for all ten items was 6.13 (SD=1.34). Scores for items 5, 6, 7, 8, 9, and 10 were above 60%. For item 4, the respective score was below 60% but above 40%. The scores for items 1 and 2 were between 25% and 40%. The score for item 3 was far below 25%. A summary of Item Response Distribution, Item Difficulty, and Point Biserial Item Discrimination results was provided.
Penn et al. (2007) [30]	10 middle school students.	Structure of matter; tools and instrumentation.	To introduce or reinforce concepts of atomic structure and the particle nature of matter to middle school age students. To demonstrate the use of electron microscopy and the concept of increasing magnification.	Two-day (12 h) program with a series of visualization-based and experiential activities.	Pencil and paper assessment.	Students demonstrated improved concepts of (1) the atomic structure of crystalline materials, and (2) that the size of an object is independent of the size of the atoms of which it is composed.
Ristvey and Pacheco (2013) [39]	21 high school teachers.	Size and scale; tools and instrumentation (AFM and STM).	To develop an understanding of nanoscience and technology concepts (NS&T) and develop plans to incorporate NS&T into the curriculum.	Yearlong *NanoTeach* teacher PD program with an intensive 2-week summer course.	Pre-, post-, and 12-month delayed posttest.	Results showed gains in teachers' content knowledge in the area of tools and instrumentation, as well as teachers' successful implementation of nanoscience and nanotechnology into their regular curriculum. Teachers further believed that learning the function and operation of the mobile AFM and STM instruments would provide a valuable resource to share with their students.
Sockman et al. (2012) [34]	300 high school students.	Forces and interactions.	How do high school students think about nanoscience within the context of gecko adhesion? What are the qualitative differences between the students who earn a higher score when compared with a lower score? What are the qualitative insights gained from essay questions that are less likely to be evident in traditional multiple choice tests in nanoscience?	A series of eight lessons based on a NanoLeap unit, Investigating Static Forces in Nature: The Mystery of the Gecko.	Embedded formative assessments; post-instruction essay.	Students tended to make comparisons not based on mathematical referents but rather in everyday terms (e.g., tiny, small), thus reinforcing the developmental need for scaffolding learning. Student performance was stronger in the representations of the physical characteristics of the gecko and weaker in accounting for the nature of the forces and interactions that occur.

(Table 1: Continued)

References	Study participants/ learners	NSET content focus	Research questions or research goals	Pedagogical approach of intervention	Learning measures/ data	Synopsis of findings
Stevens et al. (2010) [31]	High school students, middle school students, and undergraduate students.	Structure, behavior, and properties of matter.	To develop hypothetical learning progression for the growth of grades 7–14 students' models of the structure, behavior, and properties of matter, as it relates to nanoscale science and engineering.	N/A	A paper and pencil test.	A progression from empirical data that characterizes how students currently develop their knowledge as part of the development and refinement of a hypothetical learning progression was developed. Most students are currently at low levels in the progression and do not perceive the connections across strands in the progression that are important for conceptual understanding.
Taylor and Jones (2009) [28]	19 middle school students.	Size-dependent properties; surface area to volume.	Is there a correlation between proportional reasoning ability and a student's ability to understand surface area to volume relationships?	One-week instructional intervention involving investigations about surface area to volume as a limiting factor on physical and biological systems.	Pre- and post-test in proportional reasoning and applications of surface area to volume.	Results revealed a significant correlation between proportional reasoning ability and students' understanding of surface area to volume relationships. Only students who understood how surface area and volume related to each other were able to apply the concept to a scientific context. Students at a transitional level of understanding may be able to calculate surface area and/or volume but may not be able to apply or explain the concept in a scientific context.
Taylor and Jones (2013) [29]	35 middle school students, 45 high school students, and 37 high school biology teachers.	Size-dependent properties; surface area to volume.	Is reasoning ability correlated with the ability to apply surface area to volume relationships to applications in science? Is visual-spatial ability correlated with the ability to apply surface area to volume relationships in science? Could reasoning or visual spatial ability be possible predictors for applying knowledge of surface area to volume relationships within a scientific context?	5-day experience during which middle school students engaged in activities involving scale, magnification, and surface area to volume. Biology teachers taught applications of SA/V in their biology curriculum.	Pre- and post-instruction assessments in logical thinking, visual-spatial skills, and SA/V applications.	How one applies surface area to volume relationships is related to the ability to visualize and manipulate the objects spatially, and logical thinking skills. For middle school students, the ability to apply surface area to volume relationships may be predicted by components of visual spatial skills. For high school students and teachers, reasoning ability may be a possible predictor for surface area to volume relationship applications.

(Table 1: Continued)

References	Study participants/ learners	NSET content focus	Research questions or research goals	Pedagogical approach of intervention	Learning measures/ data	Synopsis of findings
Tretter et al. (2006) [13]	37 grade 5 students, 71 grade 7 students, 59 grade 9 students, 38 grade 12 students, and 10 doctoral students.	Size and scale.	What existing cognitive frameworks do students have with respect to conceptualizations of distinctly different sizes and scales? How do students' conceptualizations differ by age? How do formal education and other experiences potentially influence students' conceptualizations of size and scale? How do students' conceptualizations of scale compare with those of experts in science?	N/A	Scale of Objects Questionnaire (SOQ); a card sort activity.	Participants generally lacked distinctions of size among microscopic objects, and relative size was more easily understood than exact size. While experts (doctoral students) identified size relative to precise mathematical language, younger students were more likely to relate size to concepts learned from common experiences outside school.
Tretter et al. (2006) [15]	37 grade 5 students, 71 grade 7 students, 59 grade 9 students, 38 grade 12 students, and 10 doctoral students.	Large magnitudes of spatial scale.	How accurate are conceptualizations of spatial scale of objects and distances over many orders of magnitude? How does accuracy of spatial scale vary with age and experience from elementary school through doctoral students in science? How do experts in science mentally maneuver across many orders of spatial magnitude?	N/A	Scale Anchoring Objects (SAO) assessment.	While all participants were accurate in the realm of visible human scale, accuracy for longer distances declined smoothly as the distance increased but fell off sharply at the microscale (smaller than about 100 μm). All age groups had difficulty distinguishing between objects of the one-millionth and one-billionth scales, often listing microscopic objects for the smallest (one-billionth) unit and small but visible objects for the one-millionth scale. Older participants were able to effectively jump to alternative systems of reference for larger and smaller scales, influenced by either an instrument (SEM, AFM) or by a unit relative to that scale.
Waldron et al. (2006) [17]	1500 individuals age 6 years through adult.	Nanotechnology awareness, size and scale.	To determine public awareness and understanding of nanotechnology and their ability to assign size order to millimeter, micrometer, and nanometer scale objects.	N/A	Paper and pencil assessment, corroborated with interviews of 400 of the participants.	With the exception of those in the 14–28 year old category, over 60% of the participants reported never having heard of nanotechnology. Prior to approximately age 11 years,

(Table 1: Continued)

References	Study participants/ learners	NSET content focus	Research questions or research goals	Pedagogical approach of intervention	Learning measures/ data	Synopsis of findings
						the smallest thing an individual reports to be able to "see" and to "think of" are essentially the same. Over 40% of teens in the ages 14–17 years category were able to cite nanoscale objects, while adults in general provided responses similar to younger children.
Wischow et al. (2013) [43]	2 high school science teachers.	Pedagogical content knowledge for teaching pre-college nanoscale science.	How does implementing nanoscience content influence teachers' pedagogical content knowledge? How does teachers' PCK influence teachers' implementation of nanoscience content?	1-year professional development experience that included a 2-week intensive content and pedagogy course and academic year follow-up activities.	Interviews and classroom observations (case study design).	Teaching novel content (nanoscale science) provided a context in which the teachers made shifts in their science teaching orientations. In both case studies, teachers displayed elements of didactic/content mastery and discovery teaching orientations. Both teachers also strengthened their overall domain-specific content knowledge and connections between areas of their content domain by implementing novel content in their classrooms. Assessment was the one of the PCK knowledge bases that played little to no role in how teachers developed their nano lessons.

smaller than they actually are, although not with the same degree of difficulty relative to the human scale [13–15]. For example, Tretter et al. [15] found that for grades 5, 7, and 9 and gifted senior groups, the accuracy of conceptions of large dimensions tended to uniformly decrease as size increased, while students' conceptions of small sizes tended to remain accurate until the visible realm was passed, at which point conceptual accuracy "dropped precipitously" (p. 1080).

While it may not be surprising to find less accurate rankings among younger participants, perhaps due to the lack of having used microscopes and familiarity with microscopic and submicroscopic objects, Tretter and colleagues posited that visual cues (e.g., being able to actually see mountains, the moon, and stars) may play a role in providing points of reference for more systematic conceptualization of larger objects and distances [15]. There also appears to be a grade level turning point, prior to which students are unable to even consider the existence of objects outside the world of their experience. For example, students prior to the sixth to eighth grade levels were unable to make a distinction between the smallest thing they can see and the smallest thing they can imagine [16, 17]. Also, individuals were likely to more accurately order the sizes of the smallest things they are able to see (housefly, dust, eyelash, grain of salt) than the sizes of the smallest things they cannot see (cell, atom, bacterium, water molecule) [16]. Adults appeared to have the same difficulty with these kinds of tasks as children [17].

Tasks that involve absolute rankings of size are more difficult than those of relative ordering. People tend to be more accurate at ranking larger scale objects than smaller ones. At the small and medium scales, younger learners tend to be less accurate in their rankings than older individuals [13, 14]. Furthermore, among pre-college groups, grades 5 through gifted seniors, Tretter et al. [13] reported that students were more accurate in ranking object sizes relative to each other than in identifying their actual size. While elementary students may have lacked experience with microscopes and microscopic objects, even middle and high school groups had difficulty in accurately ranking microscopic objects.

With respect to teachers' ability to accurately rank across sizes and scales, Jones et.al [14] found that at sub-visible scales, fewer than 30% of experienced teachers and fewer than 10% of novice teachers were able to accurately name a micrometer- or nanometer-sized object. Both groups of teachers' relative rankings of the sizes of objects were overall more accurate than absolute rankings.

5.1.3 Additional influences on conceptions of size and scale

The ways in which individuals conceptualize size and scale also may be mediated by factors related to cultural influences and learning environments. For example, in a cross-cultural comparison of the effect of the system of measurement used in everyday practice, Delgado [18] found among students in grades 6–12 in the US and Mexico that the conceptual understanding of scale and measurement of Système Internationale (SI)-native students was significantly greater than their US customary system (USC)-native classmates in the same school. A significant finding in the study was that there was no significant difference between SI- and USC-native students for tasks that required the application of factual knowledge gained from formal schooling [18]. Jones et al. [19] reported similar findings from teachers' conceptions of size and scale across three nationalities: Taiwan, Austria, and the US. These researchers found that SI-native Austrian and Taiwanese teachers held more accurate conceptions of size and scale than their US counterparts. Jones et al. [14] suggested that teachers' reported in-school and out-of-school experiences (e.g., athletic competitions, map reading, building things, measuring, using microscopes, and watching media) may have been beneficial to their learning. Jones et al. [19] also found differences in the kinds life of experiences potentially contributing to learning scale, with Austrian teachers citing travel, Taiwanese teachers citing sports and reading, and the US teachers citing hobbies and sports. The Austrian teachers, who held the most accurate conceptions of scale, reported learning about scale through school activities such as estimating and calculating and making conversions among scales. Taiwanese teachers reported measuring objects and learning about scale in specific contexts such as the study of cells, while teachers from the US described memorization activities and estimating [19].

Forming accurate conceptions of size and scale also has been shown to be fostered by learning experiences that involve active or kinesthetic engagement and appeal to multiple senses. For instance, Blonder and Sakhnini [20] demonstrated, using nearly two dozen activities comprising a nanotechnology unit, that providing students with diverse and repeated opportunities to learn in active and interactive ways not only increased student interest and engagement but also had positive effect on learning. Similarly, the video "The Powers of Ten and the Relative Size of Things in the Universe" [21] has been shown to have a positive impact on middle school students' understanding of orders of magnitude and scale [22], appealing to multiple senses and using visual, verbal, and temporal representations of scale.

In addition, some researchers have explored the effect of haptic augmentation of instruction on size and scale understandings [23, 24]. For example, Jones et al. [23] found that students in both limited-haptic and full-haptic environments made significant gains in their understandings of nanometer scale. Specifically, students in both treatment groups were more likely to identify examples of nano-sized objects and describe the degree to which a human would have to be shrunk to reach the size of a virus. In another study examining the influence of haptic augmentation on science learning, Jones et al. [24] found that students who were given the opportunity to actively "touch" the viruses via haptic feedback appeared to be more interested and engaged in the educational experience. Also, the students' use of analogies increased with the use of a haptic desktop device, suggesting that this learning environment may influence the way in which the students construct their understandings about abstract science concepts.

Finally, regardless of the types of approaches or tools used, research demonstrates that understanding relationships between and among dimensions of objects in both relative and exact measures comes less from the accretion of factual information than from frequent and repeated development of skills across different contexts [25] and repeated and systematic teaching and application [18, 20, 22, 26].

While these preceding described studies have documented individuals' conceptions of categories of size, relative and absolute sizes, and examples of learning experiences and environments for diverse samples of age and experience, less research has identified and documented effective strategies in the teaching of size and scale and learning. This would suggest that the next step should be to create and assess frameworks for K-12 learning experiences to explicitly target the most effective ways for learning concepts of size and scale, akin, for example, to the Framework for Characterizing and Scaffolding Size and Scale Cognition (FS2C) that was developed by Magana et al. [26] with a population of undergraduate university students.

5.2 Learning research on concepts related to size-dependent properties

A fundamental principle related to nanoscale materials, and perhaps the most defining of all nanoscale-related phenomena, is that there are thresholds of size across which properties of a material are often governed by size. Four of the studies in this review examined students' and/or teachers' conceptions of size-dependent properties. The most common theme among studies that focused on or included size-dependent properties is the surface area and volume (SA/V) relationship. While nanoscale phenomena relating to surface area and volume relationships can best be understood in terms of the atomic and molecular composition of matter, forces, and thermal energy, we found that treatment of these concepts was generally underutilized in learning. The following studies, however, illuminate the fact that understanding factors related to size-dependent properties poses challenges to both learning and teaching, requiring individuals to push the limits of their abilities to visualize and manipulate objects in multiple dimensions.

A testament to the difficulty in understanding the significance of how and why size can affect nanoscale materials, Bryan et al. [27] analyzed secondary teachers' understanding of size-dependent properties in a year-long nanoscience professional development program. Teachers completed multiple laboratory activities and investigations of size-dependent properties, among them the synthesis and manipulation of a ferrofluid, the fabrication of a gold particle biosensor, and the synthesis and characterization of quantum dots. While researchers anticipated that following instruction, teachers' explanations of size-dependent phenomena would be supported with rationale based on forces, aspect ratios, atomic structure, and thermal energy, fewer than 20% included this level of sophistication. While many of the teachers cited examples of nanoscale properties that differ as a function of size, they were less likely to explain the underlying concepts how and why these differences occur.

5.2.1 Surface area to volume relationships

Learning about the nature of size-dependent properties requires understanding that surface area to volume phenomena at the nanoscale are often the direct consequence of an increasing proportion of atoms on the surface of a particle, relative to those of the particle as a whole. Assessing how and what individuals are able to learn about and apply abstract concepts like surface area and volume relationships has prompted researchers not only to investigate what is learned and how it is applied but also to identify the cognitive skills and kinds of reasoning that may be required and the challenges that learners may encounter.

One of the factors in being able to visualize relationships among dimensions of objects is skill in proportional reasoning [28]. As an example, in a study of a 5-day summer middle school program (n=19, ages 11–13 years), Taylor and Jones [28] found a significant correlation between proportional reasoning ability and understanding of surface area to volume relationships. Important to these researchers' findings, beyond students being able to compare sizes of cubes using correct ratio terminology, was students' increased ability to use surface area to volume arguments in different contexts. Provided figures of lakes with different surface areas, students were able to recognize that larger surface area promotes greater thermal transfer. Similarly, from drawings of fish gills of different configurations, students were able to predict that those with the greatest surface would be most efficient. Based on their findings, these researchers raised the question of how other constructs, such as visuospatial skills, might affect the learning and application of the consequences of the surface area and volume relationships in various scientific contexts.

In a subsequent study, Taylor and Jones [29] examined how middle and high school students' and teachers' reasoning skills and visual-spatial abilities influenced their ability to apply surface area to volume relationships to applications in science and whether or not their reasoning or visual spatial ability could be possible predictors for applying knowledge of surface area to volume relationships within a scientific context. Participants completed a series of assessments including the *Test of Logical Thinking*, *Storage test*, *Surface Development test*, and the *Applications of Surface Area to Volume Assessment*. The findings of this study not only confirmed their previous research [28] showing that proportional reasoning is correlated with understandings of surface area to volume but also extended the correlation to include logical thinking for older participants. The findings also indicated that for middle school participants, spatial visualization is related to the ability to understand surface area to volume concepts. Regression analysis confirmed that for high school students and teachers, reasoning ability could be a possible predictor in the ability to apply surface area to volume relationships [29].

While individuals may be able to take an intuitive approach to predicting the effect of warming of lakes, cooling of gold spheres, and the absorption of oxygen or dye across membranes based on surface area, the complexity of how and why proportional changes in surface area and volume affect the behavior and properties of materials at any scale may elude understanding until the learner has attained an appropriate level of ability to reason and to spatially manipulate multiple objects in three dimensions. For example, in a study involving 60 ninth-grade participants attending 12 weekly nanoscience lessons, Blonder and Sakhnini [20] emphasized the probability that students of this age may not have yet developed the mental skills necessary to visualize and appreciate quantitative implications of a larger cube being composed of smaller cube components. From an activity in which students visualized the individual parts of an object resembling a Rubik's cube, one student commented, "I didn't understand the connection between the Hungarian cube and nanotechnology" ([20], p. 512).

The studies elaborated in this section point to the challenges, both in learning and teaching, encountered in understanding the implications and consequences of changes in proportions of three-dimensional objects. These combined findings provide a foundation for understanding some of the factors that affect what and how individuals learn about size-dependent properties as they relate to nanoscale objects, materials, and systems. Moreover, these findings illustrate the challenges of understanding not only that the interplay of size, shape, forces, energy, and atomic structure affect properties that only emerge at the nanoscale but also how and why those changes occur.

5.3 Learning research on the nature of matter

Understandings associated with the nature of matter can be described as core and precursor concepts for NSET education. Although research related to pre-college students' conceptions regarding the nature of matter is extensive in science education, until recently, very few studies have situated the study of nature of matter in an NSET context. This contextualization is relevant because at the nanoscale, matter exhibits novel and unexpected properties, and resulting behaviors and interactions may be counterintuitive for a novice learner. In this review, we found two articles that directly addressed students' learning about states of matter in an NSET-related context.

In a study that examined learning within a middle school microscopy camp, Penn, Flynn, and Johnson assessed the students' macroscopic, microscopic, and symbolic conceptions of particles [30]. On the pretest, researchers identified three types of representations: acceptable representations of clear atomic structures where atoms had consistent sizes and shapes (n=0), unacceptable representations with no evidence of atomic structure (n=9), and unclear representations where the drawings included some indication of atomic structure but depicted that atoms lacked consistent size and shapes (n=1). On the posttest, researchers identified shifts in the same three types of representations: acceptable representations of clear atomic structures where atoms had consistent sizes and shapes (n=8), unacceptable representations with no evidence of atomic structure (n=1), and unclear representations where the drawings included some indication of atomic structure but depicted atoms lacked consistent size and shapes (n=1). These results suggest that students were able to develop an improved understanding of the idea that the size of an object's atoms is independent of the size of the object [30].

In a study by Stevens et al. [31], the researchers identified core concepts associated with models of the structure, behavior, and properties of matter through a hypothetical learning progression. Drawing on the work of Duschl, Schweingruber, and Shouse in *Taking Science to School* [32], they defined learning progressions as describing how learners may potentially construct a more sophisticated understanding of a concept over time. This might be of a sequential nature, where the progression elaborates how the understanding of one concept supports and forms the foundation for the learning of another. Alternatively, the learning progression may describe how the learner constructs a more complex model, where the knowledge of a concept becomes more sophisticated, incorporating broader ideas and connections to related topics [31]. Learning progressions qualitatively differentiate among levels of understanding, articulating the knowledge needed by students prior to developing a sophisticated understanding (herein called lower anchor) as well as expected sophisticated knowledge and ideas (herein called upper anchor). In their study, Stevens et al. defined the lower anchors and upper anchors for the hypothetical learning progression, followed by a delineation of the specific science content between the lower and upper anchors for atomic structure and related electrical forces.

To identify middle school, high school, and undergraduate students' (n=73) levels of understanding of (a) the structure and properties of matter and the sources of those properties and (b) the atomic model and the forces and interactions occurring between atoms and molecules, the researchers conducted semi-structured interviews. They found that 69 students fit the lower levels of their identified empirical progression for atomic structure including ideas of electron cloud model (n=15), Bohr/solar system model (n=13), protons and neutrons located in the center of the atom and electrons on the outside (n=29), atoms made of protons, neutrons, and electrons (n=35), atoms containing some components (n=50), atom as a sphere (n=63), and do not know (n=10). Three students who did not fit the learning progression were able to describe a solar system model of the atom but could not identify the components of the atoms (i.e., protons and neutrons). Another student described an electron cloud-like model of the atom but could not mention the names of the sub-atomic particles [31].

Regarding ideas associated with electrical forces, 35 students attempted to provide an explanation of why sodium and chlorine interact to form Cl_2 and NaCl and to describe the interactions that happen between atoms in these substances. Stevens et al. [31] identified in their empirical progression understandings such as the type of element that determines the electron configuration (n=8), valence electrons that are involved in interactions (n=18), electrons as the mediating components of interactions (n=26), electrical forces governing such interactions (n=3), an unspecified force governing such interactions (n=5), and do not know (n=40). Students placed at the lower levels of the empirical progression described an unspecified force as causing interactions between atoms, while other students identified electrical forces and attraction and repulsion between particles as the mechanisms responsible for interactions between atoms. Students placed in the most advanced levels of the progression identified the place of the element in the periodic table as related to the inter-atomic interactions. Overall, these findings as related to student learning of the structure and properties of matter suggest that many middle school and high students lack a working understanding of these concepts, limiting their ability to effectively integrate new knowledge structures needed when learning new NSET-related concepts [31].

5.4 Learning research on forces and interactions

Two of the articles we found examined the big idea of forces and interactions. These studies focused on the forces most influential in determining the behavior of substances chemically and physically at the nanoscale – electromagnetic forces. Höst et al. [33] examined the following: (1) students' pre-intervention conceptions about electric fields and how their conceptions were applied to a molecular context and (2) the influence of interacting with the multisensory visuohaptic model on students' conceptual understanding of electric fields around molecules. Prior to the learning intervention, the researchers conducted a written pre-assessment in which five upper secondary students described their conceptual understanding of electric fields and their application to molecular contexts by means of a written assessment. Findings from the pre-assessment indicated that only one student was able to meaningfully associate field lines to the charge distribution in a water molecule. The other four students were able to convey scientifically accurate understandings of an electric field but failed to apply this concept to a molecular context. Similarly, one student failed to identify that electric fields are associated with nonpolar molecules as well as polar molecules [33].

Ideas associated with electric fields around molecules were taught using a multisensory visuohaptic virtual environment where a molecule is visually rendered along with a semitransparent visual rendering of the van der Waals surface of the molecule. While students interacted with the visuohaptic model, researchers performed a think-aloud exercise and collected user analytics of students' interaction with the model. In their analysis, researchers found that tactile interaction with the model may result in the integration of the field knowledge with molecular charge distribution that allowed learners to merge physical and chemical concepts that are usually taught separately [33].

In a study by Sockman et al. [34], educational experiences related to static forces in nature were contextualized in the mechanisms associated with the ability of a gecko to adhere to surfaces despite the effect of gravity. In this context, the associated main learning objective was for students to identify what are the factors that affect the strength of the contact forces between interacting surfaces. The researchers developed a lesson called NanoLeap where students had to make observations and interpretations of how the gecko's foot interacts with surfaces and the factors that affect the strength of the contact forces between interacting surfaces. The effectiveness of the NanoLeap unit in helping students identify factors that affect the strength of the contact forces between interacting surfaces was evaluated by means of an essay assessment prompting students (n=100) to demonstrate their understanding about the underlying phenomena of gecko adhesion. Four themes were identified related to language patterns students used in response to the four prompts described above. Sockman et al. [34] concluded that the greatest common understandings among students were the surface-to-surface interactions between the gecko's setae and spatula. The greatest misunderstandings were related to knowledge of electrical forces and their role in gecko adhesion.

5.5 Learning research on self-assembly

The big idea of self-assembly has been described as a complicated array of phenomena (i.e., entropy, enthalpy, random molecular motion, and intermolecular attractions) working together under specific conditions in which materials spontaneously assemble into organized structures [11, 35]. Self-assembly is an important idea for pre-college NSET education because it is not only a process used to advance the progress of nanotechnology but also one through which natural structures on every scale are built [11].

One study in this review focused on the learning of self-assembly [35]. In this study, concepts about self-assembly were taught following two approaches: a hands-on laboratory experiment and the use of computer simulations. The hands-on laboratory experiment consisted of foam pieces (squared and circular) with magnets attached to them, floating in water. Foam pieces behave in a manner similar to electron clouds of adjacent atoms. Students were engaged in a process of experimentation where they hypothesized the forces that drive self-assembly. A second teaching method was the use of a computer simulation that represents the forces that are acting upon the atoms in examples such as insulin dimmers, fibroin fibers, microtubule rings, and formation of a monolayer [35].

A total of 120 high school students were exposed to the hands-on laboratory experiment (HOLab) described above, and half of them were also exposed to the computer simulation (CSim) as part of homework assignment. By means of an open-ended question that asked students to explain why small objects can spontaneously self-assemble into orderly structures whereas big objects could not self-assemble normally, the researcher identified five categories of explanations: repelling and polarity, charge and electronegativity, attraction and stickiness, intramolecular attraction, and responses that did not identify any factors other than size. The findings suggested that the HOLab reinforced the concepts of repulsion, having most of the students choosing responses as related to repelling, polarity, charge, and electronegativity as explanations, whereas the CSim advanced this concept to include intermolecular attractions having most of the students choosing responses as related to stickiness, attraction, and intermolecular attraction [35].

5.6 Learning research on tools and instrumentation

A big idea of tools and instrumentation at the nanoscale includes the idea that the tools used to visualize and manipulate matter at this scale (e.g., scanning probe microscope and atomic force microscope) are different from those used at other more familiar scales [11]. Thus, an important learning objective for pre-college NSET education is to identify and describe different types of microscopes and their limitations, as well as describe how the atomic force microscope (AFM) works [36]. In this review, we found four studies that focused primarily on pre-college learning of tools and instrumentation.

Learning gains associated with concepts and practices of tools and instrumentation have been measured using a variety of instruments and with two different populations (teachers and middle school and high school learners). Blonder [37] analyzed teacher knowledge about their appropriate use of vocabulary and depth of understanding of how the AFM works. She compared the performance of two groups of seven teachers each; one group had previous knowledge of NSET, and the other group members were NSET novice learners. Blonder found that teachers from both groups demonstrated significant increase in content knowledge, demonstrating richer vocabulary use as related to AFM after instruction. They also learned new and fundamental concepts regarding the AFM.

Jones et al. [36] analyzed 50 high school students' knowledge about the functioning of an AFM and the limitations of atomic force microscopy. They used constructed response questions that asked students to describe the nanoManipulator and AFM and to identify and describe different types of microscopes and students' newspaper reports. Before instruction, about 70% of the students were only able to name the light microscope, and another 20% were able to name the electron microscope. After instruction, 25% of students named the light microscope, 50% of students named the AFM, and 21% of students named the electron microscope. In addition, students' reports also included knowledge of how the AFM operates, the impact of the tip size on the images it produces, and the potential to use it to ask new scientific questions. Finally, about 25% the students described how the different-size tips alter the image of the sample visualized.

Harmer and Columba-Piervallo [38] engaged more than 100 sixth graders in a problem-based inquiry learning experience in which online materials, readings, and class sessions, along with remote access to a scanning electron microscope, were provided. Using the remote microscope, students analyzed samples and contributed with micrographs to a research database. By means of a pretest and posttest assessment, researchers identified significant differences in responses to questions associated with the uses and functionality of the scanning electron microscope. Specifically, students were able to identify that electrons help create images in the electron microscope and that an energy dispersive spectrometer was the tool in the scanning electron microscope that could identify elements in a sample.

Similarly, Ristvey and Pacheco [39] provided 21 high school teachers with hands-on experiences with a mobile AFM and a scanning tunneling microscope to image a microchip, *Staphylococcus aureus*, a polymer thin film, carbon atoms on the surface of a sample of highly ordered pyrolytic graphite, and a skin cross section. From the pretest to posttest assessments, teachers demonstrated learning gains on the big idea of tools and instrumentation (mean average score improved from 61% to 68%). Specifically, teachers learned the following: (1) the scanner moves the sample or the sensor to probe the sample surface; (2) the sensor detects the cantilever deflection, (3) the feedback system regulates the force interaction; and (4) the controller electronics records movements, controls the feedback loop, and sends the measured data to the computer.

5.7 Learning research across multiple big ideas

In addition to studies that focus on students' and teachers' conceptions within a single big idea, a few studies have examined teacher's content knowledge across a spectrum of NSET topics. For example, Kumar [40] conducted a study of NSET "general knowledge" (p. 20) of 109 prospective elementary and middle school science teachers who were enrolled in an undergraduate science teacher preparation course. Using the 10-item, multiple-choice "Nano Quiz" from the National Institute of Standards and Technology, he found that the prospective teachers, scoring an average of 6.13 out of 10 (SD=1.34), lacked an understanding of the physical scale of NSET and of the etymology of the term "nano". However, as the author himself stated in his discussion, the finding must be interpreted with caution. In particular, the Nano Quiz is not an assessment of *conceptual* knowledge but rather simple definitions and discreet facts (e.g., "What is a qubit?", "What is a Bose-Einstein condensate?"). Nonetheless, the findings highlight the necessity for prospective science teachers to develop an understanding of some general NSET concepts, particularly regarding the physical scale of nanoscience and nanotechnology, if they are to effectively design and implement NSET instruction at the pre-college level.

In the context of a sustained-contact NSET professional development program, Bryan et al. [27] examined teachers' learning of NSET concepts as well as the durability of their learning across the following topics: (a) defining and describing the nanoscale (material properties and behavior); (b) size and relative scale; (c) tools of the nanoscale (scanning probe microscopy); (d) size-dependent properties (optical and magnetic); (e) structure and design of materials (allotropes, fullerenes, and self-assembly); and (f) models and modeling. Twenty-four teachers participated in a yearlong sustained contact professional development program that included an intensive 2-week (80+ h) institute. Participants completed a 24-item pre-test, post-test, and delayed posttest that consisted of free response, matching, fill-in, and multiple choice questions, as well as questions asking for the construction of diagrams, graphs, or models, with supporting arguments of evidence or rationale. Participants showed significant gains from pretest to post- test, as well as between posttest and delayed test (delayed test administered 8 months after posttest). In addition, based on lesson plans that teachers submitted, the lesson topics taught were matched with the test items that were most likely to be covered in those lessons. Participants' performance did not differ significantly on the delayed test between taught vs. non-taught items. Furthermore, performance on those same taught vs. non-taught items on the pretest versus the posttest also showed no significant differences. In other words, the teachers did not show a systematic bias toward teaching topics they found either particularly easy or particularly difficult during the workshop.

Studies that provide an overview of teacher knowledge or studies that describe how teachers integrate related NSET topics and ideas are relevant since most of the research conducted so far explores big ideas separately. This study highlights the need to examine and measure teachers' knowledge as they learn about NSET, particularly as the number of NSET professional development programs, workshops, and activities increases.

5.8 Learning research on teachers' pedagogical content knowledge

The learning studies reviewed to this point have been organized according the big ideas of NSET and have summarized both pre-college students' and teachers' learning of NSET content. However, in the realm of teacher learning, there is an additional dimension of knowledge that is integrally related to teachers' development of knowledge for teaching NSET in pre-college classrooms: *pedagogical content knowledge* (PCK) – that is, knowledge about learners, curriculum, instructional strategies, and assessment to transform content knowledge into effective teaching [41].

Teachers undeniably play a pivotal role in the integration of contemporary, cutting-edge science in the pre-college classroom. It is an intuitive notion that teachers must have a strong, flexible, and coherent understanding of command of NSET subject matter if they are to be able to facilitate students' learning of NSET concepts. Several studies reviewed in the previous sections of this article have addressed a critical aspect of teachers' NSET learning – NSET content learning (i.e., size and scale [14, 19]; logical thinking and visual-spatial skills related to surface area to volume relationships [29]; tools and instrumentation [37, 39]). Yet, content knowledge alone is not sufficient for effective teaching. In fact, decades of research have shown that a significant component of teacher learning must include the expansion and elaboration of PCK [41]. Therefore, an aspect of NSET learning research that should not be overlooked is teacher learning, specifically the development of PCK for teaching NSET concepts in pre-college classrooms. In this section, we review a handful of studies that examine aspects of teachers' PCK.

A crucial part of teachers' PCK for teaching NSET concepts relates to knowledge of models and modeling (e.g., drawings, analogies, computer simulations, and 3-D models). Building, revising, and manipulating models are an inherent component of science and engineering practices. At the pre-college level, teachers should understand that models are particularly critical to the advancement of NSET in that they allow students to visualize structures, construct hypotheses, explain phenomena, and articulate and communicate ideas about concepts at a scale that is otherwise unreachable. In pre-college NSET education, models also serve as a pedagogical tool for teachers. For NSET education, teachers must learn to use models to not only represent and organize salient features of the content to be learned but also provide a means for students to investigate NSET phenomena in the process of learning target concepts.

Daly and Bryan [42] examined 18 secondary science teachers' reported practices of model use in NSET education after the teachers had participated in a sustained-contact professional development program offered by the NCLT. From an analysis of implemented lesson plans, responses to a written survey on model use, and post-lesson implementation reflective writings, they found that teachers reported four different uses of models for NSET instruction: (1) tool for visualization, (2) product of a student's design, (3) representation for student critique, and (4) means for investigation. The most common use of models was for visualization – that is, for students to see, watch, and/or touch a model. When teachers used models as tools for visualization, they described teaching strategies that were predominantly teacher-centered and transmission-focused. On the other hand, teachers who employed models for design, critique, and investigation described strategies in which students used models to synthesize, evaluate, and convey their own ideas through the act of designing a representation of their understanding of NSET phenomena [42].

In a case study of two secondary science teachers' PCK development, Wischow et al. [43] examined how the teachers' PCK both influenced and was influenced by their integration of NSET content into their science curriculum. Prior to implementation of NSET lessons in their science classroom, both teachers took part in a yearlong professional development program developed and implemented by the NCLT. Data included two semi-structured interviews per participant, videotaped classroom observations and field notes, teachers' written lesson plans, and teachers' reflective narratives. The suite of data sources was designed to capture a holistic picture of the teachers' PCK and construct a "PCK map" to articulate the relationship between teaching orientations, knowledge of science curricula, knowledge of students' understandings of nanoscale phenomena, knowledge of instructional strategies, and knowledge of assessment for each teacher. Analysis showed that teaching NSET provided a context in which the teachers made shifts in their science teaching orientations. In both case studies, teachers displayed elements of didactic/content mastery and discovery teaching orientations. Both teachers also strengthened their overall domain-specific content knowledge and connections between areas of their content domain by implementing novel content in their classrooms. However, PCK maps illuminated that assessment was one of the PCK knowledge bases that played little to no role in how teachers developed their NSET lessons [43].

6 Discussion and implications

From this review, it is clear that there exists a community of scientists and science and engineering educators and practitioners who are engaged in important and valuable research that examines learning in NSET education contexts. The evidence in these studies establishes that at the pre-college level, students and teachers can increase their understanding and retention of fundamental NSET concepts and practices when they engage in appropriate instructional interventions. Additionally, many of these studies are contributing to our understanding of how students learn abstract concepts of non-visible phenomena in science and when and how these concepts can be taught. For example, studies like Stevens et al. [31] provide the field with a framework of how NSET content knowledge can be aligned with current scientific concepts, along with a progression of how students learn it. Such framework is informative in designing learning experiences that help learners make connections between the ideas to develop an integrated knowledge structure that they will need to understand and explain a range of NSET phenomena, concepts, and practices.

However, it also is clear from this review that NSET education is still a relatively undeveloped field. Considering the sheer number of pre-college NSET programs and millions in funding that has been devoted worldwide to NSET education, we were somewhat dismayed by the dearth of published research on pre-college students' and teachers' learning of NSET. Further, the breadth of NSET concepts addressed in studies is rather narrow. By far, the highest concentration of empirical studies conducted to date focus on learner's understandings of size and scale and a few related concepts (e.g., surface area to volume ratio).

Yet perhaps it is a bit early to expect more published work on NSET learning. The very nature of learning studies requires an instructional context in which to examine learning. In many ways, it is a "Catch 22". The design of sound, coherent, and developmentally appropriate NSET instructional experiences needs to take learners' existing and evolving knowledge into account, providing them the opportunity to become explicitly aware of their ideas and helping them build/revise/elaborate their knowledge. However, in order to inform the design of instruction with knowledge of how learners come to understand concepts, phenomena, and practices, one must be able to examine and measure the development of their understanding of concepts, phenomena, and practices in situ. The complexity of instructional design and the time it takes to develop it cannot be underestimated. Design of sound, coherent, and developmentally appropriate NSET instruction involves iterations of testing and revising in the process of implementation.

Furthermore, teachers need to be given the time and resources to develop the knowledge bases necessary to effectively integrate and implement NSET instruction in existing course curricula. Finally, in order to examine and measure knowledge, valid and reliable NSET assessments are an essential and vital resource. Similar to sound, coherent, and developmentally appropriate instructional materials, valid and reliable assessments take a great deal of time and iterative development to construct. These need to be well aligned in order to effectively and reliably measure learning.

7 Recommendations

Several trends emerged in the studies we reviewed that lead us to make recommendations for research in NSET education. First, as a field, we need more studies that investigate NSET learning *beyond the learning of declarative knowledge*. An important component of NSET learning and understanding involves mechanistic thinking – that is, understanding and explaining why something happens. While studies exist that examine how students apply some of the big ideas to macroscale scientific phenomena, how learners understand the application of the big ideas as they relate to and explain phenomena at the nanoscale has been less explored. For example, a focus among studies about students' understanding of surface area to volume ratio is documenting what students know about changing surface area and volume relationships and their applications to real-world scenarios (capacity of lungs, gills, and intestines; warming bodies of water; and cell organelles) [28, 29]. However, what has yet to be examined is the explicit application of this concept to nanoscale phenomena – i.e., how and why surface-dominated properties relate to surface area and volume relationships (melting point, color, magnetic remanence, material defects, tensile strength, and electrical properties). Studies that provide insight into learners' development of understanding of how to use big ideas to explain nanoscale properties seems to be a logical next step.

Studying students' reasoning and explanations of why and how phenomena occur naturally should lead to examining students' understanding of the interdependence and relationship between big ideas. Of particular importance, given the interdisciplinary nature of NSET, is examining understanding of core ideas across disciplinary contexts – by emphasizing the relationships among big ideas across different scales and disciplinary contexts, students may develop deep, transferable understandings and more coherent frameworks for reasoning about how different concepts and principles interact as a system [44]. For example, in the context of learning about the behavior of ferrofluids as a size-dependent nano phenomenon, a high school level explanation would require understanding the interplay between several big ideas. Students need to have an understanding of forces and interactions – that is, magnetic fields, forces, and polarity – that some materials can be magnetized, re-magnetized in a different orientation, and/or demagnetized by external forces. However, they also need to understand the SA/V implications and how, in contrast to larger scale materials, the response and behavior specific to the nanoscale particle is dominated by the thermal energy of the atoms on the surface relative to those interior.

This means that as a field we may need to consider examining learning over a longer duration of coherent instruction in which students have an opportunity to develop deep and flexible understandings about NSET content. Currently there exists a plethora of short-duration modules, activities, and programs that report a small range of learning. Because NSET requires connections between knowledge across disciplines, longer and more coherent learning experiences should emphasize the connections of ideas both within and among domains, which in turn will require a more integrated approach to organizing instruction. As Stevens et al. noted, "The current approach tends to consist of individual units that stand alone and do not help students make the connections needed to build integrated knowledge structures" ([11], p. 708). Understanding connections among big ideas holds promise for helping students to develop explanations and reasoning for why and how phenomena occur rather than learning bits and pieces of disconnected factual information.

This recommendation applies to teacher learning studies as well. This means that professional development experiences in which we are most likely to examine teacher learning cannot be the "drive-by" variety that are likely to be ineffective in helping teachers meaningfully learning integrated NSET into pre-college curricula. Like students, teachers must be given time to develop deep, flexible, and coherent understanding of NSET content. Stevens et al. highlight teacher preparation as a significant challenge "to the goal of an NSE-educated citizenry" ([11], p. 173–178). In his analysis of the educational significance of NSET, Laherto [45] warns of the very consequences of short-duration, single-instance, ineffective learning experiences: "The sophistication of the concepts of [NSET] easily leads to superficiality in instruction and the risk of misrepresenting the content matter. Furthermore, the simplified use of images and other visual models can mislead learners into false models of direct sense perception and epistemological misunderstandings" (p. 170). Moreover, as teachers develop the professional knowledge for teaching NSET, they must have the opportunity and time to adapt their instruction to reflect what they have learned and analyze the outcomes of their new/refined knowledge and practice (e.g., student learning). This suggests that professional development and teacher preparation should not only emphasize the development of content knowledge and PCK but should also provide ongoing support and promote reflective practices. If NSET concepts are to be meaningfully integrated and taught at the pre-college level, then those who design and offer pre-college teacher learning experiences should heed the recommendations from decades of research on what constitutes effective and high-quality professional development (for a summary of these professional development design principles, see [27], p. 88) as well as lessons learned from extant professional development programs (e.g., [46, 47]).

Finally, we suggest that NSET education researchers consider a design-based research approach [48–50] for NSET learning research. Designed-based research "simultaneously pursues the goals of developing effective learning environments and using such environments as natural laboratories to study learning and teaching" ([50], p. 200). This approach to research requires an iterative cycle of design, development, and field testing of the learning experiences and instructional materials. Each stage of design, development, and field testing is focused on the ultimate goal of building and refining an instructional experience that supports learners in their development of conceptual understanding and skills. We need to examine how learners understand core ideas in NSET – not simply at one point in time but also dynamically as their understandings evolve in the context of sound instructional interventions.

8 Conclusion

Science, engineering, and technology at the nanoscale level are emerging fields that have significant implications for the future of pre-college STEM education. Over the last decade, we have witnessed the emergence of a growing body of research on pre-college NSET learning. In an effort to characterize the state of research to date on NSET learning, we have identified and summarized these studies for this review – specifically the peer-reviewed, published research studies that report pre-college student and teacher NSET learning data and analyses. From this review, it is clear that (1) those engaged in NSET education learning research have begun building the foundation for a broader agenda of integrated NSET into pre-college curriculum; (2) at the pre-college level, students and teachers can increase their understanding and retention of fundamental NSET concepts and practices when they engage in appropriate instructional interventions; and (3) the design of sound, coherent, and developmentally appropriate NSET content and practices requires a considerable amount of time and effort. From this growing body of scholarship, we are beginning to find out what NSET concepts students and teachers are learning as well as the experiences that are helping them learn these concepts. This scholarship is critical in building a vision of pre-college NSET education and providing guidance for what concepts should be taught across the K-12, when these concepts should be taught, and what is the nature of learning environments that best promote coherent and durable understandings. Thus, advancing pre-college teaching and learning of integrated, contextualized, and transferable NSET content knowledge and practices as well as in-depth, long-duration, design-based NSET educational research will require the collaboration of many stakeholders and resources. Science educators, learning scientists, assessment researchers, and STEM practitioners must work together to orchestrate efforts to fulfill this important, timely, and relevant goal.

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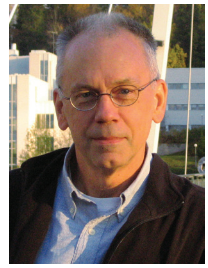

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