MODESTUM EURASIA Journal of Mathematics, Science and Technology Education, 2023, 19(12), em2361
ISSN:1305-8223 (online)
OPEN ACCESS Review Article https://doi.org/10.29333/ejmste/13834

Nanoscience and -technology in secondary education: A systematic literature review

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Received 05 July 2023 ▪ Accepted 21 October 2023

Abstract

This article provides a review of empirical research into nanoscience and -technology (NST) education at the secondary school level with regards to (a) teaching strategies or laboratory experiments implemented and evaluated for their impact on student learning about nanotechnology aspects, (b) concept inventories and methods used to assess students' conceptual understanding, as well as (c) students' conceptions and learning difficulties. A database search was used to identify corresponding studies published over the last decade (2012-2021) of which eleven were included in the synthesis for further analyses after screening for eligibility. The analysis revealed that learning difficulties regarding NST topics such as the differentiation between size and scale, the surface area to volume ratio or size dependent properties are widely prevalent among learners according to the current state of the literature. While our analysis identified emerging perspectives for future research with regards to the development of psychometrically characterized concept inventories in particular and empirical investigations into students' learning progressions on nanoscience concepts in more general, a huge effort has already been put into the development of teaching concepts or laboratory experiments suitable for secondary school classrooms.

Keywords: nanoscience, nanotechnology, secondary education, empirical research, students' conceptions, literature review

INTRODUCTION

The field of nanoscience and -technology (NST) is finding applications and driving progress in areas such as engineering, medicine, chemistry, and physics (Ernst 2009; Gardner & Jones, 2009; LeBlanc, 2018; Tretter, 2006). New ways of drug delivery (Petros, 2010), treatment of diseases (Panyala, 2009), material development (Wagner, 2007) as well as the advancements in the areas of computing and electronics (Schwierz, 2010) are just a few of the possible confrontations with nanoscience any student may encounter in their career (cf. Jones et al., 2015).

In their 2010 review article, Hingant and Albe (2010) review curriculum developments, research on students' conceptualizations of nano-related concepts, haptic tools to teach nanoscience as well as professional development of secondary school teachers. They further provide an in-depth definition of "nano" and "nanoscience", which, in the following, we go along with. In short: We perceive the notion "nanoscience" as the science of matter that refers to the nanometric scale while "nanotechnology", on the other hand, refers to the application of nanoscience principles, e.g., in order to engineer and manufacture new materials, devices and systems with unique properties and functions. A comprehensive overview of the interdisciplinary range of nanotechnologies is provided by Jones et al. (2013). Since both nanoscience and nanotechnology are closely related and often appear intertwined, especially in educational settings (cf. Chopra & Reddy, 2012; Manou et al., 2021), they are loosely combined under the label NST, which we will use in the following. As introduced by Blonder and Sakhnini (2012) as well as Tretter (2015), we refer to NST subareas:

(a) surface-area-to-volume ratio,

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Contribution to the literature

- The provision of a comprehensive overview of teaching strategies regarding nanoscience and -technology at the secondary school level that have been subjected to empirical evaluation for their impact on students' conceptual understanding.
- Investigation and compilation of innovative assessment methods used in empirical research to explore secondary students' understanding of NST concepts.
- Identification of common learning barriers for secondary school students in the area of NST, to provide a better insight into learners' cognitive processes and to inform the development of future teaching approaches.

(b) the nanometric vs. the micrometric scale,
(c) size and scale, and
(d) process skills regarding experimentation, tools, instrumentation in the ensuing sections.

Hingant and Albe (2010) further emphasize a lack of studies on NST as a socio-scientific issue. Obviously, there have been different directions pointed out on how to develop appropriate curricula and much discussion of the essential aspects of NST that should be taught (Hingant & Albe, 2010). However, a "need for empirical research to produce more informed decisions" (Hingant & Albe, 2010, p. 128) on that same account has been identified at that time.

RESEARCH BACKGROUND

By reviewing the impact of haptic learning tools, Hingant and Albe (2010) unveiled the agreement on the positive impact of using haptic learning tools in combination with atomic force microscopy on learning and engagement of the students a decade ago. But they also uncovered the need and demand for further development of devices, especially as a strategy for targeting said size and scale concepts (Jones et al., 2003, 2004, 2006; as cited in Hingant & Albe, 2010). Revisiting this account, the question arises what progress has been made regarding teaching sequences, laboratory experiments or methods targeting students' understanding.

Ghattas and Carver (2012) examined the–back then–"current literature related to the integration of nanoscience in school science curricula as early as preschool through higher education" (p. 272) and concluded that, in light of the demand, there is a rather small portion of successfully integrated educational activities surrounding nanotechnology (cf. Ghattas & Carver, 2012). Jones and her team also reviewed the educational approaches in nanotechnology on a precollege level in 2015. Whilst there appear to be multiple approaches such as tools, applications, or analogies in addition to their corresponding knowledge types, students' conceptions on the nanoscale seem to be counterintuitive (Jones, 2015). Furthermore, in their 2015 article, Bryan et al. (2015) studied empirical research on precollege and teacher education regarding nanoscale science, engineering and technology education, in particular: Content knowledge and practices. They conclude that there is an existing community of scientists and science educators who are doing valuable research, but the examined field is still "relatively underdeveloped" (cf. Bryan et al., 2015). The sum of this research beckons an update of those aspects. Hingant and Albe (2010) additionally set explicit focus of their review on the professional education of secondary teachers detailing empirical work on teachers' professional development on nanotechnology programs (Bryan et al., 2007; Daly & Brian, 2007; Daly et al., 2007; Hutchinson et al., 2009; Tomasik et al., 2009) or describing their design for example as an online environment (cf. Tomasik et al., 2009). Accordingly–in order to broaden this information–the review presented in this article will no longer focus on the professionalism of teachers, but rather focus on the impact of (interdisciplinary) teaching sequences or laboratory experiments on student learning. Consequently, while Hingant and Albe's (2010) investigation revealed difficulties regarding the concepts of size and scale, in this article, we extend on their review by exploring the progress that has been made in addressing secondary students' learning difficulties targeting NST aspects over the last ten years, beyond the concepts of size and scale.

Besides research into science teachers' professional development in the area of NST, there have also been several programs to mentor, inspire or motivate undergraduate or graduate students including, for example, space programs (cf. Erdman et al., 2019; Friend & Beneat, 2013; Luo et al., 2019) or outreach programs (Claville et al., 2019; Healy & Rathbun, 2008), which do significantly describe the wide range of the term "nano". Like stated beforehand, this research approaches education specifically concerning the nanoscale size instead of widening the term further to "smaller than usual" in layman's terms. Moreover, those programs show repeatedly how large the age span of learners of nanotechnology is: Starting in primary or elementary schools (cf. Peikos et al., 2020; Sharpe, 2015) up to graduates (cf. Peikos et al., 2020; Peng, 2012) or teacher education (cf. Jones et al., 2008, 2013).

RESEARCH QUESTIONS

Because of the versatile dynamic of the field, there is a need for an update on the status-quo regarding educational research as presented by Hingant and Albe (2010), in particular with a focus on secondary education: Therefore, we report the results of a systematic literature review on NST education at the secondary school level in this paper. A special focus in this investigation is set upon empirically supported research. Hence, in this article, we address the following research questions:

1. What
   a. teaching strategies and
   b. laboratory experiments

   aimed at the secondary school level have been implemented, and evaluated for their influence on students' understanding of NST concepts?
2. What
   a. instruments, i.e., concept tests, have been evaluated and
   b. further methods–besides concept tests–have been used to probe

   secondary students' understanding of NST aspects on a conceptual level?
3. What learning difficulties do secondary level students encounter while being taught NST?

In the subsequent sections, the paper continues with a description of our methodology to explain our research process. This will be followed by the literature analysis concerning the individual research questions. Finally, the results will be contextualized and discussed, leading to the identification of

(a) research gaps and

(b) subareas that could be explored in further research.

METHODS

To answer our research questions, a systematic literature review was conducted. The methodology underlying a literature review can be described as "an explicit and replicable search strategy with studies based on predetermined criteria" (Pincheira & Alsina, 2022, p. 4). To ensure a valid and sound procedure that is in line with up-to-date standards regarding literature reviews, we closely followed the steps outlined by *preferred reporting items for systematic reviews and meta-analyses* (PRISMA) 2020 instructions (Page et al., 2021); alongside their respective extension statement PRISMA-S (Rethlefsen et al., 2021). PRISMA 2020 statement is a well-established instance in contributing guidelines for researchers to enable standardized approaches for reviewing literature in a given research field (cf. Gericke et al., 2022; Sibgatullin et al., 2022). They provide detailed descriptions for every stage of the review, from the very start (identification of records in databases) to the final sample that is used to clarify the research questions. The guidelines consist of a 27-item checklist and a four-phase flow diagram (identification, screening, inclusion, report) to enhance the transparency and completeness of reporting. PRISMA procedure involves the following steps:

1. **Planning the review:** The first step is to clearly define the research questions and establish inclusion as well as exclusion criteria for the literature search.
2. **Conducting the search:** Here, a systematic and comprehensive search of multiple electronic databases is performed, along with a hand-search of relevant articles.
3. **Selecting studies:** Studies are screened and selected based on the inclusion and exclusion criteria. This step is conducted by multiple reviewers to minimize bias.
4. **Extracting data:** Data from the selected studies is extracted systematically, using previously designed data extraction forms and protocols.
5. **Synthesizing results:** The findings of the selected studies are synthesized and analyzed to answer the research questions.
6. **Reporting the review:** The results of the analysis are presented and discussed in a coherent manner.

In the following subsections, we will depict in detail every step we conducted during our research according to these guidelines. A flowchart of the entire review process is provided in **Figure 1**.

Search Strategy

In the identification step (cf. **Figure 1**) the online databases Scopus by Elsevier and Web of Science by Clarivate Analytics were searched because of the index of impact they constitute (SJR and JCR, respectively). Our search strategy was to first apply a broad and non-restrictive search-string to obtain a comprehensive sample of research in NST education. To this end, we combined the following three aspects of learning scenarios with the Boolean operators AND as well as OR provided by the databases:

1. The target group ("who is learning?") was filtered using keywords such as learner, student, pupil, etc.
2. The learning environment ("where/how are they learning?") was filtered with keywords such as lesson, course, assignment, etc.
3. The learning content ("what are they learning?") was determined by the term nano.

While the three different aspects were combined with the operator AND, the keywords within each aspect were combined with the operator OR. This way it is ensured that the requirements for the desired learning scenario as a whole are met while still obtaining a great variety within each of its aspects. To further verify that

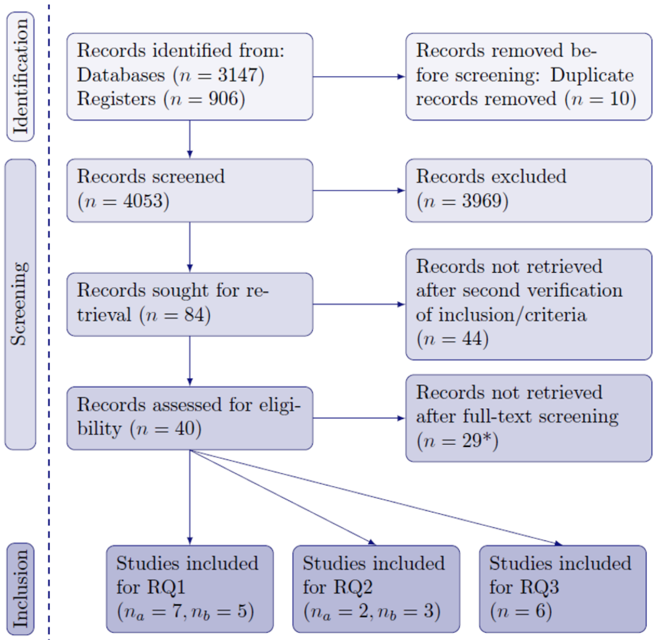

Figure 1. Flowchart of study selection process according to PRISMA guidelines (*22 records were removed due to exclusion criteria E2 (3), E3 (5), E4 (9), E5 (5), & seven further publications were removed due to poor quality) (Source: Authors' own elaboration)

different notations are also found, ambiguous keywords were followed up with an asterisk. In either syntax, the asterisk represents any group of characters including no characters; for example, concept* matches with concept as well as concepts and conceptual. Both databases were searched on 27 April 2022.

Our full search-string for Scopus reads "TITLE-ABS-KEY((learner* OR student* OR pupil OR novice OR undergraduate*) AND (lesson* OR course* OR assignment* OR "problem solving" OR learning OR test* OR concept* OR idea OR qualitative OR quantitative OR assessment OR evaluation OR empirical OR validation OR instruction) AND nano*)" and returned 3147 results (cf. **Figure 1**). Our full search query for Web of Science reads ((ALL=((learner* OR student* OR pupil OR novice OR undergraduate*) AND "(lesson* OR course* OR assignment* OR problem solving OR learning OR test* OR concept* OR idea OR qualitative OR quantitative OR assessment OR valuation OR empirical OR validation OR instruction) AND nano*)" and returned 904 results.

Study Selection & Screening Process

Before the preliminary sample consisting of 4053 articles went into the screening process, inclusion and exclusion criteria were established. To assure that only articles of high quality are eligible for our review we exclusively considered papers that were published in a peer-reviewed journal. In addition, both the paper and the abstract were required to be written in English and the publication date was limited to the years 2012-2021. Furthermore, in relation to our research questions, it was necessary that the investigation presented in the article

Table 1. Overview of exclusion & inclusion criteria applied to sample

Criterion & definition	
Inclusion criteria	
I1	Investigation scope relates to conceptual understanding of nanoscience education research
I2	Investigation is aimed at secondary/high school level
I3	Investigation scope relates to empirical research
I4	Abstract & paper in English
I5	Published in peer-reviewed journal
I6	Publications year between 2012-2021
Exclusion criteria	
E1	Investigation is not focused on nano (atomic model)
E2	Investigation is aimed at educational levels above secondary schools
E3	Investigation does not provide empirical evidence
E4	Reviews & articles that are not journal publications, e.g., published in books or conference series

(a) can be categorized as nano science education research,

(b) was aimed at secondary or high school level, and

(c) comprised empirical research.

Consequently, we excluded reviews as well as articles that

(a) did not focus on nano aspects of education,

(b) addressed educational levels above secondary schools,

(c) did not present any empirical evidence, and lastly

(d) are not journal publications.

An overview of our inclusion and exclusion criteria is presented in **Table 1**.

In summary, an article was deemed eligible if and only if all inclusion criteria (I1-I6) were met and no exclusion criterion (E1-E4) was met. For example, the articles concerning the frameworks FS2C for characterizing size and scale cognition by (Magana et al., 2012) as well as the size and scale framework SSF by (Kong et al., 2017) were excluded since they focus on undergraduate education (E2). On a more complex note, for example, an article by (Tirre et al., 2018) addressed exclusively nature of science aspects of NST education, which are beyond the scope of our review and thus did not explore learning difficulties or students' conceptual understanding–it was therefore removed because inclusion criterion I1 was not met.

Title-abstract screening

After removing duplicates in the preliminary sample, the retrieved list of 4,053 publications was subjected to two rounds of a rigorous title-abstract screening (cf. **Figure 1**). For this stage, every article was marked with either 1 (if included) or 0 (if excluded) by two independent raters, according to our inclusion and exclusion criteria. Dissenting judgements occurred in about 1.1% (45 out of 4,053) of the cases. If the uncertainty about inclusion or exclusion could not be resolved through a discussion the article was left in the sample until the next screening step. In most cases this procedure was conducted when it was unclear whether the study focused on nanoscience education itself or rather its implications for closely related topics. For example, in an article by (Sharpe & Andreescu, 2015) the authors investigated the educational effects of a nanoscience laboratory experiment that introduces students to "portable nanoparticle-based paper sensors for rapid analysis and field detection of polyphenol antioxidants" (Sharpe & Andreescu, 2015, p. 1). In this case a discussion of the article led to the exclusion because the nano-aspects of the presented laboratory experiment focused solely on chemical reactions and thus it does not constitute a study of nanoscience and technology in the sense elaborated in our introduction.

Full-text screening & coding scheme

In the last screening step (cf. **Figure 1**), the remaining 40 articles that passed the title-abstract screening were retrieved and the full text was reviewed. To this end, a previously designed protocol form was filled in, in a double round analysis. In this protocol we documented different features of the articles, e.g.,

1. surface characteristics such as title, publication date, country, author(s), journal name and the DOI,
2. methodological information such as aim of research, study design, sample characteristics and research tools, and
3. empirical results.

The gathered information was then used in a follow-up discussion among all authors to assess the suitability of each article, leading to the elimination of 29 more articles. Among other reasons, in this final step publications were removed that were either off-topic, for example by focusing on affective learner characteristics and beliefs rather than conceptual understanding of NST aspects (cf. Chen et al., 2012; Guasch et al., 2020; Sahin & Ekli, 2013); or because they did not provide sufficient empirical evidence (cf. da Silva et al., 2016; Moraes, 2012).

In summary, the final sample of the study comprises eleven articles of which seven contribute to a clarification of RQ1a, five to RQ1b, two to RQ2a, three to RQ2b and six to RQ3. In this regard, it is noteworthy that some articles were assigned to multiple research questions at once.

LIMITATIONS

Even though the aforementioned guidelines are helpful in circumventing methodological flaws, there are limitations inherent to systematic literature reviews that need to be considered.

First and foremost, there is a huge variety of databases to choose from and the list of indexed journals in those databases is under constant change. Thus, the necessity to select specific databases inevitably entails the risk of excluding relevant research. Moreover, it is apparent that conducting a literature review requires taking a snapshot of the existing literature and thus only a status quo can be described. Additionally, every search-string that is applied to a database is inherently limited by the absence of standards when creating abstracts, keywords, and titles. For example, researchers may present studies on NST education without explicitly stating the educational aspect of their work in any of the search fields. Consequently, such works will not be detected by any search-string filtering for educational works.

Another limitation relates to the reviewed literature not being assessed from a bibliometric viewpoint and thus the research impact of the presented studies is not considered. In short: The presented works are analyzed on a purely descriptive level–measuring their relevance, quality, and impact in the field of NST education is far beyond the scope of a literature review.

Finally, we want to address a non-methodological limitation, implied by the nature of education sciences in general: educational studies are invariably linked to the respective country's curriculum. As such, the samples of the herein discussed studies exhibit a large degree of heterogeneity caused by variety of countries, especially in terms of prior knowledge. This should be kept in mind when comparing results described in literature.

RESULTS

In **Table 2**, we give a descriptive overview of the studies included in the synthesis. In the following passages we will provide a synthesis of the published research related to our research questions in detail.

Table 2. Descriptive overview of studies included in synthesis & contributing to a clarification of research questions (some articles provide clarity on various research questions & are examined from different perspectives in describing findings related to those questions in following sub-sections & mixed-method approaches are classified under both qualitative & quantitative categories)

Reference	Research approach		Sample size	RQ1a	RQ1b	RQ2a	RQ2b	RQ3
	Qualitative	Qualitative						
Blonder and Sakhnini (2012)	x		60	x				x
Delgado et al. (2015)	x	x	32	x	x		x	x
Favero et al. (2019)		x	44		x			x
Hudson-Smith et al. (2019)	x	x	47		x			
Lin and Lin (2016)	x	x	720	x				x
Schneider et al. (2019)	x		80		x			

Table 2 (Continued). Descriptive overview of studies included in synthesis & contributing to a clarification of research questions (some articles provide clarity on various research questions & are examined from different perspectives in describing findings related to those questions in following sub-sections & mixed-method approaches are classified under both qualitative & quantitative categories)

Reference	Research approach		Sample size	RQ1a	RQ1b	RQ2a	RQ2b	RQ3
	Qualitative	Qualitative						
Senocak et al. (2021)	x	x	10	x	x	x	x	x
Sripongwiwat et al. (2016)	x	x	83	x				
Tarng et al. (2018)		x	67	x				
Tretter (2015)		x	207	x		x		x
Yayon et al. (2012)	x	x	6				x	

Results Regarding RQ1a: What Teaching Strategies Aimed at Secondary School Level Have Been Implemented, & Evaluated for Their Influence on Students' Understanding of NST Concepts?

Table 3 provides a summary of the teaching strategies developed and implemented in the publications of our synthesis.

Blonder and Sakhnini (2012) developed an educational module to support students' understanding of NST concepts "size and scale" and "surface-to-area-volume". They used a wide spectrum of teaching methods including game-based education, simulations, multimedia, storytelling and project-based approaches. All those methods were part of a two-part module,

Table 3. Papers included in analysis of RQ1a (for an in-depth description of teaching concepts & their impact on students' conceptual understanding of NST topics see body text)

Reference	Pedagogical approach	Content covered	Setting of implementation
Blonder and Sakhnini (2012)	Game-based learning, visualization & multimedia, films, simulations, models, PBL, storytelling, & narratives.	• Size & scale • Surface-area to volume ratio (SA/V)	60 9th graders in terms of a study-sequence in school. Two-part module consisting of firstly 9h/9 lessons teaching concepts & secondly guiding student groups in a final project in nanotechnology (3 lessons).
Delgado et al. (2015)	A PBL approach was used: Situated learning, social interaction, & use of cognitive tools.	• Size & scale • Distinction micro, nano, subnano • Identification of objects on scales	32 students: 19 6th graders & 13 7th & 8th graders in a 12h curriculum unit included in a summer science camp.
Lin and Lin (2016)	Comparison of a 10-page booklet vs. a 109-page comic.	• Lotus effect & application • Biological compass • Targeted therapy • Nano-photocatalysts • Definition of nanotechnology • Properties on nano-scale materials • Measurement tools • Possible risks on NST	Classes in each school were randomly selected & assigned to text–or comic–group: 30 participants (text group 12 students & comic group 18 students).
Senocak et al. (2021)	3-day educational program on NST including theoretical & practical parts using discussions of effects, presentation, synthesis, & experimentation, digital presentations (i.e., Skype) has been implemented.	• Magnetic nanoparticle synthesis • Polymeric nanofiber fabrication • Imaging of produced nanofibers	10 sophomore students (5 male & 5 female) selected randomly in a public high school.
Sripongwiwat et al. (2016)	Teaching model developed with constructionism & neurocognitive based theories.	• Basic of nanotechnology • Nanotechnology in nature • Activated carbon with nanotechnology • Nano products inventing tools • How to invent nano products • Uses of nanotechnology • Nanotechnology products	Case study: 2 grade 11 classes: 1 experimental group (49 students) & 1 control group (34 students).
Tarng et al. (2018)	Virtual reality combined with situated learning theory: Instructional videos, teaching aids, achievement tests, presentation, & virtual assembly.	Fullerene production & its nanostructure analysis	67 senior-students pre-post-test with control group (32 students) & experimental groups (35 students).
Tretter (2015)	There have been 5 consequential days with 55 minutes blocks of instruction constructed out of theoretical & practical units via author implemented. There were periodical teacher-led discussions to process explorations & experiences.	• Size & scale • Properties of matter • Particulate nature of matter • Tools in NST • Modelling • Dominant forces • Technology & society • Self-assembly–molecular forces	207 students (aged 16-18 years) in 3 schools.

wherein 60 students participated. The first part of the module consisted of nine teaching lessons introducing the students to nanotechnology, concepts within the nanoscale as well as significance, implications and applications of nanomaterials and nanotechnology. The second part of the module lasted three weeks and the participants could choose methods freely to further deepen their input about NST and prepare a presentation of a chosen application in a project-based setting (cf. Blonder & Sakhnini, 2012). The findings indicated that the game-based learning activity as well as the simulation did not engage the students enough to generate significant learning gains (Blonder & Sakhnini, 2012).

Tretter (2015) evaluated an instructional unit consisting of five consequential units (of 55 minutes each) targeting the "big ideas in nanoscience" (p. 34), such as size and scale, properties of matter, particulates of matter, dominant forces, tools in NST, modelling, technology and society and self-assembly, respectively. A total of 207 high school students between the ages of 16 and 18 participated in the instructional sequence. The particulate units were performed by the author, having the physics teacher of the individual class assisting the instruction. Inquiry questions aimed at students' conceptions with the nanoscale and their accuracy as well as the possible impact of a rather short-term instructional tool (cf. Tretter, 2015).

From the evaluation results no significant changes became apparent between pre- and posttest. Therefore, it appears that students hold a constant conception of size for objects at the visible scale. Still, there were clear changes in conceptual thinking about scale for non-visible objects. The students held more accurate notions about objects at the micro- and nanoscale. The total posttest growth outcomes on the used CNI–*conceptions of nanoscale instruments*–as described in RQ2a–showed that student knowledge substantially grew across the spectrum of concepts measured.

Furthermore, a 12h instructional unit for middle school students was developed by Delgado et al. (2015). Their research describes the design process, application and evaluation of a 12h unit for size and scale, implemented in a summer science camp for middle school students using a construct-centered-design-process for curriculum and assessment. A project-based learning (PBL) approach was adopted to design the curriculum materials and guide the instructional approach: Situated learning (different activities, e.g., swabbing surfaces for bacteria, visualization of their own cheek cells under optical microscope), social interaction and the use of cognitive tools that amplify what students learn (e.g., learning technologies, computer simulations). The result: The curriculum unit constitutes a source of instructional activities that have been tested to achieve statistically and educationally significant learning gains (cf. Delgado et al., 2015).

The study of Sripongwiwat et al. (2016) aimed to examine the effect of the developed constructionism and neurocognitive-based teaching model on students' science learning outcomes and creative thinking (problem-solving). The topics used for the application of the model are: Basic knowledge and understanding of nanotechnology, its incidences in nature, relation to activated carbon as well as invention, uses and tools of nano-products (Sripongwiwat et al., 2016).

The result of the study showed no difference between groups in the dependent variables, except for science process skills before the intervention. However, after the intervention, all dependent variables, namely the three science learning outcomes and creative thinking in the experimental group (n=49), were significantly higher when compared to the control group (n=34). Said learning outcomes, which improved with the constructionism-model, are related to the general content knowledge, process skills and attitude. Thus, the teaching model–consisting of the six steps: Boost attention, gather information, understanding, organize thoughts, idea clarification and idea testing–is found to have a more significant effect on the overall science learning outcomes and thinking than the traditional model of presenting via a teacher centered introduction, instruction and conclusion: "It is concluded that the developed constructionism and neurocognitive based teaching model […] is able to enhance the science learning outcomes and creative thinking of grade 11 students" (Sripongwiwat et al., 2016, p. 15).

Lin and Lin (2016) studied the impact of texts versus comic booklets on 10th graders for the purpose of learning NST: A sample of 720 students were part of the study, where a 10-page booklet vs. a 109-page comic conveying the same content were tested on different learning-achiever-types. One method focused on textual representation through text structures, examples, questions and titles, while the other emphasized visual and textual representations to build knowledge of science occurring in interesting daily life contexts through dialogue, humorous cartoons, and scientific pictures. Both groups made significant improvements in their knowledge of NST through reading the assigned media and both media were similarly effective in terms of communicating scientific concepts as measured in the public knowledge of nanotechnology test. For high achievers the text booklet seems to be more beneficial, while the comic book was found to be more beneficial for medium achievers. Concerning the main reasons for student's engagement in reading printed media: Whilst high achievers were affected mostly by the topic of the media and low achievers mostly by the type of the media, medium achievers perceived both type and topic similarly. However, the findings indicate that science comics are not more effective than science texts for students of all achievement levels.

Table 4. All didactical features that were reported are presented & associated learning difficulties observed in respective studies are sorted by sub-areas (a cross indicates that difficulties arose in this area with corresponding didactical feature of specific type)

Main (didactical) feature(s) of teaching strategies	References reporting implementation	NST S-1		NST S-2		NST S-3		NST S-4	
		A	PR	V	DS	RS	S-DP	U	F
Game-based	Blonder and Sakhnini (2012)	x		x		x	x	x	
Visualization/multimedia	Senocak et al. (2021)	x	x			x	x	x	
	Blonder and Sakhnini (2012)			x	x		x		
	Tarng et al. (2018)	x		x				x	
Simulations	Blonder and Sakhnini (2012)			x			x		
	Tarng et al. (2018)	x	x	x		x			
Models	Blonder and Sakhnini (2012)			x	x	x	x		
PBL	Delgado et al. (2015)	x	x	x		x	x		
	Blonder and Sakhnini (2012)			x	x	x	x		
Storytelling/narratives	Blonder and Sakhnini (2012)	x	x		x	x	x		
	Lin and Lin (2016)	x					x	x	x
Theoretical lesson-input	Tretter (2015)			x	x	x	x		
	Delgado et al. (2015)	x	x	x		x	x		
	Tarng et al. (2018)	x	x			x	x	x	
	Sriponwiwat et al. (2016)		x		x	x	x		
	Senocak et al. (2021)						x	x	
Practical lesson-input	Tretter (2015)	x	x	x	x	x	x	x	x
	Delgado et al. (2015)	x		x		x	x	x	
	Blonder and Sakhnini (2012)			x	x	x	x		
	Senocak et al. (2021)						x	x	
Constructionism & neurocognitive	Sriponwiwat et al. (2016)		x		x	x	x		
VR	Tarng et al. (2018)	x	x	x	x	x	x		

Note. S-1: Surface-area-to volume ratio; S-2: Nanometric vs. micrometric scale; S-3: Size & scale; S-4: Process skills; A: Abstraction; PR: Proportional reasoning; V: Visibility; DS: Distinction between scales; RS: Relative size; S-DP: Size-dependent properties; U: Unfamiliarity; & F: Focus

Taking a step away from haptic reality Tarng et al. (2018) explored virtual reality as a teaching strategy. The aim of their research was to develop and evaluate the learning effectiveness of a virtual laboratory that facilitates learning about fullerene production and its nanostructure analysis. Especially concerning invisible or inaccessible subjects, virtual reality can be a helpful tool, since the immersive learning potential takes a big part in creating learning gains (cf. Dengel & Mägdefrau, 2018). The implementation of the virtual laboratory–which we will explore more closely in RQ1b–showed a definite increase in motivation and interest leading also to an increase in knowledge (cf. Tarng et al., 2018) measured via a questionnaire survey of 15 questions on a 5-point Likert-scale after the instruction.

Lastly, Senocak et al. (2021) implemented a 3-day educational program on NST, developed to increase high school students' academic knowledge and awareness levels of NST concepts like size-dependent properties, innovations and applications of nanotechnology, size and scale, characterization methods, classification or fabrication approaches of nanomaterials. The program consisted of theoretical and practical parts (magnetic nanoparticle synthesis, polymeric nanofiber fabrication, imaging of produced nanofibers) and was conducted at a university.

Interim Discussion to RQ1a

In light of searching for already established best practices it is of interest to regard the above detailed educational developments in connection to RQ3–namely, which topics and difficulties they cover, which are given prematurely in **Table 4**. Further explanation concerning the learning difficulties in detail will follow in the discussion to RQ3.

Table 4 shows there has been significant work on the topics of size and scale as well as the surface-area-to-volume-ratio. The strategies mainly targeting the visualization of concepts such as game-based or multimedia approaches reside within the work of Blonder and Sakhnini (2012), with exception of the virtual reality setting (Tarng et al., 2018). Thus, in the area of exploring visualization techniques of abstract concepts there is also great potential for further investigation.

Results Regarding RQ1b: What Laboratory Experiments Aimed at Secondary School Level Have Been Implemented, & Evaluated for Their Influence on Students' Understanding of NST Concepts?

Here, we provide an overview of the developed laboratory experiments concerning NST for students of secondary education. **Table 5** provides a summary of NST experiments developed, implemented and evaluated in secondary education so far.

As described previously, Delgado et al. (2012) used experiences that can usually be found within a laboratory implemented as a part of their lesson-plan within a PBL approach, thus a closer look at this part of their investigation contributes to RQ1b. Activities to conceptualize nanoscale and nanoscience understanding of the participants such as sketching their own cheek cells under an optical microscope, swabbing surfaces for bacteria and incubating them on growth medium in Petri

Table 5. Papers included in analysis of RQ1b (for an in-depth description of laboratory experiments see body text)

Reference	Key finding(s) related to RQ1b
Delgado et al. (2015)	Visualization & conceptualization through: ● Swabbing surfaces & incubating bacteria growth ● Use of an optical microscope ● Modelling effect of surface roughness
Favero et al. (2019)	Three-part experiment: ● Synthesis of gold nanoparticles ● Purification & analysis of samples' optical properties, focusing on noncovalent interaction with metallic ions ● Realizing a chemo sensor for cations using nanoparticles synthesized to analyze an unknown sample containing bivalent or monovalent metal cations
Hudson-Smith et al. (2019)	Development of macroscale TEM model that uses cyanotype paper for "imaging" & is constructed of a UV light source, a tube, & photosensitive paper. Investigation of TEM-micrographs' properties including thickness contrast, diffraction contrast, plan view, & tilt series imaging. Four activities: ● Identification of mystery objects ● Sizing objects from their micrographs using a scale bar ● Sketching structure of a mystery 3D object from acquired tilt series images ● Developing unique micrographs with objects of students' choice & predicting features of resulting images
Schneider et al. (2019)	Synthesis of fluorescent carbon quantum dots from lemon juice has been used. For separation procedure chromatography was applied. Investigation of fluorescence happened via a TECAN SPARK 10 M multimode reader.
Senocak et al. (2021)	As a part of educational program second of 3 consequential days was used to implement experimental procedures: ● Magnetic nanoparticle synthesis by using iron(II)-sulphate & iron(III)-chloride solutions with adjustments in pH & temperature ● Observation of those particles in interaction with a magnet ● Introduction of electrospinning & nanofiber fabrication ● Observation & collecting of nanofiber samples for further processing via electrospinning ● Preparing samples for atomic force microscopy

dishes, as well as testing for bacterial presence on different parts of the building and modelling the effect of surface roughness, were built into the instruction. Sequencing them in a fashion, so that students "first encountered familiar objects [… and] then progressively interacted with smaller […] objects" (Delgado et al., 2015, p. 55) was meant to illustrate and explain the nanometric scale. Thus, the main targeted subareas of NST are size and scale and proportional reasoning. Concerning students' understanding the goals of developing awareness towards the sub-macroscopic scale and its impact on the world, as well as understanding of proportional differences and relative sizes could be improved (Delgado et al., 2015).

Favero et al. (2019) developed and implemented a three-part-project for students with good chemical knowledge in a high school setting concerning the investigation of properties of gold nanoparticles after synthesis. The project included the synthesis of the gold nanoparticles, their purification and analysis of their optical properties as well as a realization of a chemo sensor for cations using the synthesized nanoparticles on an unknown sample demonstrating size-dependent properties (cf. Favero et al., 2019). Showing positive results in understanding (via survey questions afterwards targeting content) and handling of the process by the students, it is yet another example of the positive impact on learning effects that active interaction with the subject provides.

Schneider et al. (2019) developed and implemented a synthesis laboratory experiment for students of secondary education level as well. Through a so called one-pot-synthesis of fluorescent carbon quantum dots from lemon juice, they aimed to provide an accessible method for schools, and, in particular, a hands-on experience of NST experiments whilst finding an answer to the question whether practical courses can help with regards to fostering students' understanding of complex chemical and physical concepts. This research targeted the subareas of NST application and students' awareness within the subareas of size-dependent properties and size and scale. Their research took place via a qualitative field study, where 80 high-school students in three high school chemistry classes in Switzerland (ages 17-18) as well as four teachers participated and tested the 2h laboratory experiment. The data of 35 of the 80 students was analyzed at the end via a formative pre-posttest assessment. And at least concerning their research the answer was: They can and "the calculated average effect size [concerning increase in knowledge through practical courses] was 0.76, which is in the range of a medium- to large-effect size after Cohen" (cf. Schneider et al., 2019, p. 543).

Senocak et al. (2021) also included practical setting in parts: those parts consisted of guided activities by three of the authors like magnetic nanoparticle synthesis, polymeric nanofiber fabrication and imaging of said fibers, therefore mostly correlating to the subareas of size-dependent properties, size and scale and forces and interactions.

The overlapping impression is that the participants positively viewed their experience with the educational programs–nanoparticle synthesis was regarded as the most enjoyable activity. However, the students voiced the opinion that more activities (and with shorter

Table 6. Papers included in analysis of RQ2a (for an in-depth description of instruments see body text)

Reference	Concept tests	Answer format
Senocak et al. (2021)	NanoIS–Nanoscience information scale	21 items answered by true, false, or no idea
Tretter (2015)	SOQ–Scale of objects questionnaire CNI–Conception of nanoscale instrument	SOQ: Ranking objects from visible to atomic scale CNI: Scenarios paired with statements-agreement via Likert scale

duration) would improve the program (cf. Senocak et al., 2021).

Interim Discussion to RQ1b

In summary there are three types of chemically founded syntheses within our sample of studies, which is most likely due to the high intersection of NST to the chemics-education of secondary students'. This overlap on one hand suggests the exploration of said intersection intrinsically. Especially concerning the subareas of size-dependent properties these model experiments are achieving learning gains. On the other hand, the above presented research shows the gap of missing laboratory or experimental developments with different subjects underneath such as physics or biology, which could correlate more directly to subareas like the surface-area to volume ratio or the differentiation between the scales themselves. The exploration of different angles in the experimental setting can also be a starting point for future research of targeting learning difficulties more specifically, which have been underrepresented as of yet (i.e., relative size or SA/V).

Results Regarding RQ2a: What Instruments, i.e., Concept Tests, Have Been Evaluated on Secondary Students' Understanding of NST Aspects on a Conceptual Level?

Concept tests are known to play an important role in pedagogical science–especially in uncovering learning difficulties and student understanding. Specifically established and evaluated tests grasping at conceptual accuracy and working knowledge (cf. Lindell et al., 2007) deliver the foundation for developing educational units that tend to the learners needs (cf. Zenger & Bitzenbauer, 2022). **Table 6** provides a summary of the teaching strategies developed and implemented so far.

Tretter (2015) developed and evaluated the so-called CNI, which consisted of eight scenarios. Each scenario is paired with a final question and focused on one of the big ideas in NST such as "size and scale, properties of matter, particulate nature of matter, […]" (p. 34) and so on. Participants could assign their level of agreement on a Likert-scale from -3 to 3 in each scenario to three responses of which only one corresponded to a correct rationale. To apply a metric to the system the scores are summed up and normalized in addition to an overall scenario-normalizing to a range of ±1. In a computer-generated simulation of random responses the overall distribution of the CNI showed a normal distribution with skewness=-0.03 and kurtosis=-0.10, a mean of 0 and a standard deviation of 0.137, proving the system stable and reliable (cf. Tretter, 2015, p. 38). Because "the CNI is grounded in an expert consensus of the big ideas in nanoscience for high school students (content validity evidence), returned overall pretest results showing no difference from random as expected (construct validity evidence), and the metric developed from CNI has a normal distribution that satisfies a key assumption for a number of statistical techniques" as well as a "Cronbach's alpha of 0.79" it can be considered a useful tool (Tretter, 2015, p. 43).

Another concept test by Tretter (2015), the *scale of objects questionnaire-nano* (SOQ), has been used to measure conceptions of sizes of objects from human scale to sub-macroscopic scale: "SOQ-nano required each participant to select one of 12 scale ranges from <10-9 m to 101–102 m in increments of one order of magnitude" (Tretter, 2015, p. 37). Using a test-retest reliability-test (content conceptions targeting the visible scale contrasting to the invisible nanoscale) for SOQ-nano the instrument is considered reliable (cf. Tretter, 2015). On the targeted scale concerning distinctions between micro- and nanoscale SOQ produced highly apparent distinctions in the posttest, effectively measuring the conceptual achievements of the students. One has to mention that, because of the nature of the pretest–as to rank objects to scale–, the mistakes made by the students appear to be pairwise and thus suggest confusion beforehand. This indicates that the method is a better fit to discovering group tendencies than averaging concepts (cf. Tretter, 2015).

Senocak et al. (2021) developed an educational program for high school students on NST. They used a mixed method design consisting of quantitative pre- and posttests as well as a qualitative interview study for the evaluation. The quantitative tests encompassed

(a) *nanoscience information scale* (NanoIS) to measure conceptual knowledge and

(b) *nanoscience & nanotechnology awareness questionnaire* (NNAQ) to measure NST awareness, whereas the former allows to explore students' conceptions.

NanoIS includes 21 items such as, for example, "a nanometer is 1,000,000 (1 million) times smaller than a meter" (Senocak et al., 2021, p. 99), which are answered on a true-false-no idea-scale. Schönborn et al. (2015) deliver arguments in favor of the tool's validity and reliability.

Table 7. Papers included in analysis of RQ2b (for an in-depth description of instruments see body text)

Reference	Method(s) used
Delgado et al. (2015)	Semi structured interview protocol
Senocak et al. (2021)	• Nanoscience & nanotechnology awareness questionnaire (NNAQ) • Educational program evaluation form (EPEF) • Interview protocol
Yayon et al. (2012)	• Video tapes • Exams • Quiz • Written artefacts • Semi-structured interviews

Interim Discussion to RQ2a

Especially concerning NanoIS of the study by Senocak et al. (2021) it arose that the tool itself–for it being not the main focus of the study–was not sufficiently evaluated. The tool is described and applied in detail, but the significance and validity was put into the background. The authors explain that the tool is a derivative of nano-knowledge instrument tool of Schönborn et al. (2015) developed back in 2015. Besides limiting and adjusting a few questions to relevancy of NST-topic there have not been major changes to the original. Hence, further research analyzing the psychometric quality of the tool seems necessary. Concerning the discovery of group tendencies both tools out of Tretter's (2015) research in 2015 (SOQ-nano and CNI) are valuable and reliable tools already, showing promise for further implementation.

With respect to NST concepts covered in the concept inventories developed over the last decade, we observe size and scale and properties of matter as a prior focus. This suggests that further research might develop items specifically suited to assess students' conceptual understanding of size-dependent properties or forces and interactions as topics, especially in combination with the already existing model experiments, as shown in the results concerning RQ1b targeting those subareas.

Results Regarding RQ2b: What Further Methods–Besides Concepts Tests–Have Been Used to Probe Secondary Students' Understanding of NST Aspects on a Conceptual Level?

In this section, we review, which further methods have been used to probe students' conceptual understanding of NST aspects. **Table 7** provides a summary of the different methods used beyond concept tests to probe students' understanding of NST concepts so far.

Yayon et al. (2012) used a matrix to categorize their students' understanding in terms of chemical bonding. The elements relevant to describe the understanding of chemical bonding are nanostructure, electrostatic interaction between charged entities and energy aspects related to bonding. Each of these elements is refined into simpler and smaller pieces of knowledge, which are then divided into six levels of knowledge building upon each other in addition to one describing an overview. Within these levels some entries are grouped together in clusters as they relate to each other. These grains of knowledge are put into a matrix. Said matrix was then used to analyze several artefacts of students over the course of nine months. Each statement in class or answer to an interview question or exam question was then connected to an element in the matrix and coded as correctly used elements of knowledge (black), inconsistently used elements of knowledge (grey) or incorrectly used elements of knowledge (diagonal line). Finally, coded information of one test is put together in one column, with the lines representing the elements of the matrix. Another column then presents another date or artefact analyzed. With this observation tool an overview over the learning progress concerning interactions, properties of matter aka nanostructure and energy can be obtained (cf. Yayon et al., 2012).

The Nanoscience and Nanotechnology Awareness Questionnaire (NNAQ), using a 5-point Likert-type assessment for 20 items, as well as education program evaluation form (EPEF), verifying questions via a 5-stage agreement chart, used by Senocak et al. (2021) evaluated the instructions in questions from a mostly affective point of view. Thus, the items included range from "I can tell how nanotechnology will affect my life in the future" (see NNAQ) to "the intensity of the education was appropriate" (see EPEF) as described by Senocak et al. (2021, p. 99). Both surveys are adaptable for evaluation of various topics and are designed for posttest-settings.

Beyond the listed questionnaires, Delgado et al. (2015) as well as Senocak et al. (2021) used interview strategies to probe their students' conceptions. Either semi structured interviews, which both induct quantitative and qualitative questions (Delgado et al., 2015) or closed-ended questions (Senocak et al., 2021) were found to be helpful in assessing students' conceptions specifically targeting the subareas relative and absolute size. The interview questions of the latter were–as stated before–aimed at the evaluation of an educational program and were conducted one week after the intervention. Consisting of subdimensions like organization, trainer, material, environment and process they possess high adaptability for different programs (Senocak et al., 2021). This also in some way eludes students' conceptions instead of targeting them as underlying tones to affective questions.

Table 8. Papers included in analysis of RQ3 (for an in-depth description of laboratory experiments see body text)

Reference	Key finding(s) related to RQ3
Blonder and Sakhnini (2012)	Abstraction in context of surface-area-to-volume ratio (SA/V) & distinction between nanometric & micrometric objects proved to be difficult.
Delgado et al. (2015)	Two distinct groups of students–one using their pre-held knowledge (a), other grouping size by using instruments to visualize objects (b)–held difficulties in ordering scales, relative size, & absolute size. 43% accurately ordered mm, μm, & nm. 45% correctly ordered objects like housefly, dust, eyelashes, etc. 7% correctly ordered atoms, water molecules, bacteria, cells, etc. 20% estimated micro- and nanoscale objects accurately in terms of human body. All ages struggle to come up with objects of give sizes & accuracy of estimation of size concerning micro- and nanoscale is very low (no percentage mentioned).
Favero et al. (2019)	Predicting sensor behavior with different ions. Realization (like focus on steps) & accurate handling of methods & equipment proved to be difficult. As a result, two groups needed to restart experiment.
Lin and Lin (2016)	Some difficulties in understanding contents of media because of lack of prior knowledge & basic scientific terms as well as the high-coherence concerning comic-text.
Senocak et al. (2021)	Students struggle with size-dependent properties of nanostructures.
Tretter (2015)	No clear difference between nanoscale & microscale concerning concept size & scale such as dependent properties or relative size. By addressing Cohen's d (signifying differences from small growth in knowledge d=0.2 to large growth d=0.8) scenarios concerning size & scale showed least growth between pre- & post-test ranging in numbers from 0.22 to no growth in knowledge at all.

The tests used by Yayon et al. (2012) were put together to form an intricate matrix as described beforehand. The methods to get there, though, consisted of class-observation via video tapes, exams, a quiz, written artefacts, and semi-structured interviews, too.

Interim Discussion to RQ2b

A common ground for further inquiries regarding the probing of students' understanding appears to be the interview structure, which is found in all three concerning papers. Targeted subareas to NST so far are: Relative and absolute size, properties of matter and interactions and energy, which lay important groundwork. In looking to the future, adapting the tests to missing subareas like size and scale, surface-area-to-volume-ratio or size-dependent properties would be intuitive. The matrix of Yayon et al. (2012) for monitoring learning developments is promising in that field, but still needs to be assessed for validity using larger samples. To date, due to the small sample comprising only six students, however, assertions in terms of implementation and execution are difficult. Furthermore, "the matrix contains only canonical elements of knowledge and no alternative conceptions", which provides, "a major limitation of the tool" (Yayon et al., 2012, p. 261).

What the studies by Delgado et al. (2015) and Senocak et al. (2021) described in this section have in common is that the analysis of students' understanding was not the central aim. For example, the interviews conducted in their studies focused mainly on affective learner characteristics, while the exploration of student understanding was marginal.

Results Regarding RQ3: What Learning Difficulties Do Secondary Level Students Encounter While Being Taught NST?

To develop efficient and effective learning tools one has to recognize the core difficulties that are widespread among target group learners with regards to the subject under investigation. Six studies of the final synthesis provided insight into difficulties secondary school students encounter while being taught NST (cf. **Table 8**).

Two reoccurring difficulties seem to reside within the concept of surface-area-to-volume ratio and the distinction between the nanometric and micrometric scale (Blonder & Sakhnini, 2012; Tretter, 2015). For example, "students may enter the instruction with pre-existing concepts that the range of sizes in the invisible realm is equally large as the range in the visible realm" (Tretter, 2015, p. 45) and even if there is positive learning development, after the instruction used, it is still a recurring difficulty. Additionally, Tretter (2015) showed that some students "hold some incorrect prior conceptions that [...], may be a barrier to fully grasping the promise and limitations of nanoscience" (p. 45). Such barriers included the phenomena scaling dependent on surface-area to volume ratio (SA/V) and the general concept that "scaling differential influences different phenomena" (Tretter, 2015, p. 45). In the study of Blonder and Sakhnini (2012) the students' interest shifted according to the used teaching method and in turn influencing difficulty in understanding, because of abstraction and lack of visibility. In tune with this result "movies and the simulations [...] helped understand the two concepts" (Blonder & Sakhnini, 2012, p. 511) of surface-area-to-volume-ratio and size and scale. Also, the teaching method of a Hungarian cube game dealing with SA/V was described as "unclear and abstract" (Blonder & Sakhnini, 2012, p. 512) hindering the students' understanding. Concepts such as proportional reasoning, surface-area vs. volume on nano-scale and the

Table 9. Overview of learning difficulties that are widespread among secondary school students as identified from our literature review

Subarea to NST	Learning difficulties
Surface-area-to volume ratio	Abstraction of topic hinders understanding & creates fear of tackling topic on a superficial note. Also, proportional reasoning within subarea shows significant abstractness thus being hard to imagine for students.
Nanometric vs. micrometric scale	Lacking visibility of scales restricts students' perceptual understanding in terms of clarity & vividness. Therefore, coherent & sustainable distinction between scales fails.
Size & scale	Relative size creates confusion, because of mentioned preconceptions regarding transferability of visible to invisible scales. Size-dependent properties could not be predicted in turn.
Experimental aspects	Unfamiliarity of procedures limits transfer of knowledge into practice & thus hinders learning gain. Lack of focus onto procedures due to said unfamiliarity or difficulty of process also inhibits lasting transfer of learned concepts.

nanometric scale itself inhabit abstraction within their nature and, therefore, are difficult to grasp for students.

Also, the classification into relative sizes (Delgado et al., 2015), and dependent properties specific to the nanometric scale were discovered as a source of student difficulties (Senocak et al., 2021). Specifically, Delgado et al. (2015) showed that the categorization of objects into relative sizes formed a striking obstacle for the participants. Another difficulty has been revealed in the study of Senocak et al. (2021) who showed that students struggle with size-dependent properties along the nanoscale. However, the authors did not provide further information relating to the nature of said difficulty.

On the account of more haptic difficulties Favero et al. (2019) on the one hand discovered that the handling and treatment of equipment in NST context generated confusion and difficulties among learners: For example, lack of thorough cleaning of surfaces prior to experimentation leads to uncertainties in measurement and students are often not sufficiently aware of such details. Their 3-part laboratory sequence consisting of the synthesis, purification and application in a chemo sensor of gold nanoparticles suffered some setbacks within their first synthesis-approaches because of the described unfamiliarity with the necessary procedures (cf. Favero et al., 2019).

Interim Discussion of RQ3

In summary, four overarching subareas of NST creating learning difficulties have emerged from empirical research into secondary school teaching of NST published in the literature over the last decade (cf. **Table 9**).

As mentioned before, one possible reason for students' difficulties in grasping the concept of the surface-area-to-volume-ratio could be the abstract nature of the topic–similar arguments have already been brought forth in research on related topics outside NST (cf. Zenger & Bitzenbauer, 2022). Students in many cases struggle with concepts that are difficult to visualize or where the link to their established conceptions is weak. A similar reasoning can be applied to the difficulties that were found within the topic of "proportional reasoning" as well as "size and scale". If the understanding of the proportion already fails, it appears difficult to develop ideas about size-depending properties or interactions. Also linking into the same pool of difficulties is the distinction between the nanometric and micrometric scale. Not only the problem of not being able to see the scales with the naked eye, but also in parts the mathematical distinction between the scales proved to pose hurdles that need to be overcome in learning. Regarding this aspect a more rapt focus on attention to mathematical details in physics education could be a possible solution to counteract the difficulties and lay groundwork for further inspections of scales.

DISCUSSION

Future Nanoscience Education Research & Practice

The numbers alone suggest: NST education–especially concerning secondary education–is a rather young and unexplored field. Nevertheless, it stands to be a field full of potential.

The overarching ideas of NST such as concepts about size and scale or dependent properties and forces (cf. Blonder & Sakhnini, 2012; Senocak et al., 2021; Tretter, 2015) have been discussed and confirmed in heaps. Our research revealed further width and depth throughout NST education to be necessary. In the above interim discussions, we already discussed overarching commonalities in the respective papers contributing to our research questions and identified research gaps in the respective areas of NST education.

Beyond that, emerging perspectives for both NST education research and practice are suggested by our systematic literature review, which are addressed in the following: Concepts such as size and scale, the surface-area-to-volume-ratio and the distinction on the scales–particularly between micro and nano–are topics whose conveyance needs deeper pursuit in both intensity and empirical method. This also involves the challenge to exemplify abstractions, visualize invisible sizes and demonstrate size-dependent properties in more pronounced ways.

Already good headway has been made alongside the variety of pedagogical approaches with direct impact on classroom practice, ranging from instruction units (Blonder & Sakhnini, 2012; Senocak et al., 2021; Tretter, 2015); via project base approaches (Delgado et al., 2015; Hudson-Smith et al., 2019); to constructionism

(Sripongwiwat et al., 2016); or more unconventional ways like science-comics (Lin & Lin, 2016); or virtual reality (Tarng, 2018). Likewise, along the lines of laboratory works the progress is noteworthy. However, our review suggests that presentations, modelling exercises and simulations, in particular considering virtual or augmented reality would be preferable to convey NST. In summary on this account: Introducing equipment for experiments, the actual conceptual transfer, high coherence of literature and the immersive quality of digital experiences need to be assessed deeper in the future with regards to support classroom teaching of NST at the secondary school level. Whilst the subareas of surface-area vs. volume, nano- vs. micro-metric scale, size and scale in terms of relative size and dependent properties, and process skills have all been targeted at least superficially so far, concept inventories as of yet focus primarily on size and scale, model experiments focus on size dependent properties and the process itself and teaching sequences set the most focus in parts similarly onto size dependent properties but also properties of matter without the attention on the scales. Therefore, neither do the concept inventories correlate sufficiently to the developed teaching sequences, nor is there dependable data concerning the distinction between the scales or the concept of SA/V, beyond the presented research. Broadening and tweaking according to this revelation can be a perspective to draw for further investigation within this field.

Another emerging perspective–that might just target exactly the above-mentioned issue–is the apparent lack of psychometrically characterized concept inventories to monitor student learning. We encountered three empirically evaluated concept tests published in the literature over the last decade (cf. Senocak et al., 2021; Tretter, 2015). However, either the encountered concept tests were not sufficiently evaluated on a psychometric level (Senocak et al., 2021; Yayon et al., 2012) or they did not cover all observed and demanded subareas of NST (Tretter, 2015). Hence this promotes an apparent gap within the field to be addressed in the future.

Comparison to Status of Quantum Science Education Research

Similarly, to the just reviewed field of nanoscience education, quantum science education research is a young, fairly uncharted ground (cf. Bitzenbauer, 2021; Krijtenburg-Lewerissa et al., 2017). At the moment, both areas are following typical trajectories–with not very many publications from rather isolated teams (cf. Anderson et al., 2017). Thus, an increase in publications in addition to growing specialization, i.e., by the establishment of specific journals, is to be expected.

For another resemblance to quantum science education research our review revealed a rather large number of content-focused work–already during the screening process and continuing forward–and we expect to be able to observe a "a shift in the research focus from more content-specific work to [more numerous] empirical studies on the teaching and learning" (Bitzenbauer, 2021, p. 17) in the forthcoming years as well. Additionally, not only depth and width are of interest to future research, but also intersections within this multidisciplinary field are a possible way to tackle the area exclusively. A logical next step, in the interest of unravelling such developments, might be a bibliometric analysis.

Likewise, quantum and nanoscience are well on their way into tomorrow's curricula, if not already practiced, and therefore urgently need empirically supported material on both (mis-)conceptions and methods beyond the current status quo: In particular, in line with this research, considering that "students hold classical thinking" (Krijtenburg-Lewerissa et al., 2017, p. 14) in both fields and reach their limits when confronted with quantum and nanoscience precisely for this reason.

CONCLUSIONS

A look at the growing field of NST educational research has revealed not only certain sub-areas of NST with which students still struggle, but also several tactics for pursuing research, such as bibliometric analysis, or filling gaps, such as the development and empirical implementation of concept inventories. Based on this research there are already promising pedagogical approaches and laboratory sequences, but this by far does not limit the need of an area as young and unexplored as NST education to the already existing research. On the contrary, next to the already mentioned significant gap in concept tests, there are the emerging fields that need to be filled, i.e.,

- studies targeting the learning difficulties concerning size and scale, surface-area-to-volume-ratio and further abstract concepts like relative size,
- studies targeting difficulties such as proportional reasoning and size-depending properties, and
- teaching strategies that include visualization of abstract concepts more variedly.

Taking all those aspects into account further inquiry along all the lines of conveying NST to secondary students–especially focusing on presentational means–is awaited eagerly.

Author contributions: All authors have sufficiently contributed to the study and agreed with the results and conclusions.

Funding: No funding source is reported for this study.

Ethical statement: The authors stated that the study reports a systematic literature review and hence, does not require an ethics committee approval.

Declaration of interest: No conflict of interest is declared by authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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