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Nanosciences and nanotechnologies learning and teaching in secondary education: a review of literature

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This literature review provides an overview of recent studies on the introduction of nanosciences and nanotechnologies in secondary education. Four salient research topics have emerged: questions and reflections preceding curriculum development on nanosciences and nanotechnologies lessons; research on students' conceptualisations of nano-related concepts; the use of haptic tools to teach nanosciences and nanotechnologies; and professional development for secondary schools teachers. In a final critical discussion, the lack of studies in the literature considering nanosciences and nanotechnologies as a socioscientific issue in secondary education is emphasised. In addition, implications for future research as well as suggestions for nanosciences and nanotechnologies curriculum development are considered.

Keywords: nanosciences; nanotechnologies; secondary school; science education; science curriculum reform; new contents

Introduction

Nano. Over the last few years, this prefix has invaded scientific literature. Although the limits of the fields of nanosciences and nanotechnologies are blurred, and despite controversies ignited by their development, it is widely recognised that they have begun, and will continue in coming years, to have broad social and economic implications. Considered as the anchor of the next industrial revolution by the US National Science Foundation (NSF) among others, governments of many countries are currently making huge efforts to be at the forefront of nanoscale science and engineering research. For example the US government, through the National Science and Technology Council, launched in the 2001 fiscal year the National Nanotechnology Initiative (NNI) involving 25 federal agencies to coordinate federal nanotechnology development. Indeed these emerging sciences and technologies raise many questions. In particular, they have sparked off educational reflections. To fuel them, the NSF through for instance the National Centre of Learning and Teaching (NCLT) in Nanoscale Science and Engineering strive to introduce nanos into science curricula and have funded research on their development in secondary school and undergraduate courses. Consequently, and partly due to NSF grants, science education research on nanoscale science has been developing for a few years.

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Purpose

Throughout this review of the literature, we are attempting to map studies looking closely at the introduction of nanosciences and nanotechnologies into secondary school curricula. Accordingly, we are striving to provide the reader with a snapshot of this emerging field in science education that may undergo major expansion in years to come.

Although the question of nanosciences and nanotechnologies teaching is being tackled worldwide, the insight given in this overview follows a US perspective. The reason for this is as follows. The US is currently very active in this field and seems to play a leading role in its development. Consequently, research results and propositions to reshape curricula have mostly been considered in the context of the US educational system.

Nevertheless, science educators from other countries are also concerned about the introduction of nanos in secondary schools. For example the last French school programme project for the second year of high school starting from 2010 explicitly plans to ask teachers to deal with 'nanochemistry' in their lessons. This demand to teach nanosciences and nanotechnologies at this level requires the exploration of how they can be meaningfully introduced in secondary schools.

Our aim is thus to identify the salient directions in which nanosciences and nanotechnologies in secondary school education research is currently making its way and to organise and synthesise findings. We start by presenting our methodology. Then we will successively elaborate on the four different key strands that emerged from our reviewing of the literature on nanosciences and nanotechnologies education in secondary schools. Consequently, the second part deals with the reflections preceding any proposition of nanosciences and nanotechnologies instructional sequences. We will then turn to work on nano-related conceptions developed to design relevant curricula. The next section pertains to learning tools designed to approach and delve into nanosciences and nanotechnologies. In the fourth part, we will give an insight into research, casting light on and questioning teachers' professional development in relation to nanosciences.

Methodology

As nanosciences and nanotechnologies are at the heart of this work, we questioned the meaning of these terms before starting to collect research articles. In fact, the choice of a definition is bound to entail consequences for our selection of keywords.

Definition

There is obviously no denying that nanosciences and nanotechnologies focus on the study of nano-sized objects. However, there is currently no consensus on what can be considered as nano and what is excluded from this field. The definition of nanosciences and nanotechnologies varies according to contexts and authors. The object of our work is by no means to make an all-comprehensive census of existing definitions. However, selecting one of them is not a neutral action. As Vinck (2009) puts it, different actors (researchers, companies, institutions) have different interests and support different definitions accordingly. To Vinck, financial resources (grants for research or industrial development), public support or opposition, and constraints (legislation, standardisation, development programmes) are at stake and come along with definitions.

As we write it, ‘nano’ refers to the nanometric scale. Thanks to the development of tools such as the Atomic Force Microscope (AFM), scientists and technologists are nowadays able not only to observe but also to manipulate nano-objects. Nevertheless, in focusing on scale, one needs to define clearly the frontiers of the field: what is the upper limit of size for an object to be nano? Should all dimensions of the object measure a few nanometres or is one enough? These questions remain controversial. In addition, many definitions underline the fact that nanosciences and nanotechnologies study phenomena on a scale where properties differ significantly from those on a macroscopic scale. This, once again, emphasises the importance of scale.

Furthermore, the existence of two different technological approaches, top-down or bottom-up, contributes to fuelling debates surrounding the definition of nanosciences and nanotechnologies (Vinck, 2009). The first ‘top-down’ approach refers to miniaturisation. Nanosciences and nanotechnologies developments follow a trend initiated decades ago. By way of contrast, the bottom-up technological approach consists of building objects by assembling molecules or aggregates. This approach goes in the opposite direction of miniaturisation: it starts from molecules to create bigger objects.

Others characteristics of nanosciences and nanotechnologies are also put forward as people attempt to define them. In particular, it is often mentioned that at the molecular level the different traditional disciplines (physics, biology, chemistry etc.) can share common objects of study. Nanosciences and nanotechnologies are thus considered as intrinsically interdisciplinary. Finally, nanotechnologies are part of the ‘Converging Technologies’ along with Biotechnologies, Information and Cognition put forward in NSF-funded reports (Roco & Bainbridge, 2002). As their authors explicitly enhance their plans to develop them so as to ‘improve human performance’, some argue that this aspect cannot be omitted when defining nanotechnologies and are vocal in their ethical concerns (Dupuy, 2004).

Finally, many assert that nanotechnologies open up new possibilities for the development of electronics, new materials, medicine, the chemical and pharmaceutical industry, biotechnology, agriculture and so on.

Corpus elaboration

For the purpose of this work, we did not aim ‘to settle’ the awkward question of defining nanosciences and nanotechnologies. Rather, we left it to the authors to select their own definition. Nonetheless to carry out our research of articles, we had to make a choice of keywords. As our goal is to sketch a picture of the recent studies carried out in the emerging field of nanosciences and nanotechnologies education, we opted for nanoscience(s), nanotechnology(ies) and nanoscale along with teaching and education. This somewhat arbitrary decision inescapably entailed bias for our review. Indeed, by entering words with the prefix nano, we were bound to encounter solely research claiming interest in this field. As a result, we certainly overlooked articles that were related to nanoeducation but for which authors, for whatever reason, had not put up this link.

To gather articles, we referred to the (Educational Resources information Database) ERIC data base and reviewed papers from various French, English and US peer-reviewed journals – *Science Education*, *International Journal of Science Education*, *Journal of Research in Science Teaching*, *Aster*, *Didaskalia*, *Journal of Science Education and Technology*, *Research in Science Education*, *International Journal of Science and Mathematics Education*, *American Educational Research Journal*, *Review of Educational Research*, *Educational Evaluation and Policy Analysis*, *Review of Research in Education*, *Journal of Curriculum Studies, Studies in Science Education*. We also visited selected Internet websites that led us to consult different conference proceedings (for the National Association for Research in Science Teaching (NARST) and of the American Society for Engineering Education (ASEE)) as well as the *Journal of Nano Education* created in March 2009.

To add coherence to the corpus of articles collected, we decided to limit ourselves to secondary education. We also chose to exclude articles that simply involve the description of an innovation without a sound theoretical framework. In spite of this sorting, the resultant corpus is based on a variety of documents with differing status. The content of any work presented here must thus be regarded accordingly.

Finally, the selected articles share at least two things: they consider that the question of nanos introduction in science curricula is worth studying. They also aim at influencing, orienting or changing the learning and the teaching of nanosciences and nanotechnologies – related notions.

In our attempt to give an insight into this emerging field of science education, we distinguished four main and different directions of research to which the different articles were related:

- Questions and reflections preceding curricula development on nanosciences and nanotechnologies;
- research on students' conceptualisations of nano-related concepts;
- the use of haptic tools (tools rendering the sense of touch) to teach nanosciences and nanotechnologies; and
- professional development for secondary school teachers.

We now scrutinise in turn each of these aspects.

1. Questions and reflections preceding the development of nanoscience instructional sequences

Throughout this section, attention will be given to the nagging questions preceding any design and implementation of a 'nano-curriculum'. The first question relating to introducing any innovation can be framed as follows: why is it deemed necessary to devote time and energy in proposing something new? Accordingly, the different arguments put forward to legitimate the introduction of nanoscale sciences and technologies in secondary school curricula will be presented here. Furthermore, once people are convinced that there is a need to add nanos to school programmes more questions arise. In particular, decisions have to be taken concerning the most appropriate topics to teach. Indeed nanosciences and nanotechnologies encompass a vast collection of knowledge. Choices have to be made and priorities identified to select contents valuable for students. Finally, some authors have considered the introduction of nanosciences and nanotechnologies in secondary schools as an opportunity to reform widely the US Science, Technology, Engineering and Mathematics (STEM) education (Schank, Krajcik, & Yunker, 2007).

1.1. Arguments to justify the introduction of nanosciences and nanotechnologies in classrooms

All the articles vetted in this review converge on one point: it is worth exploring the possibilities of introducing nanosciences in secondary schools. However, there may be various different reasons to justify it. The preliminary questions bound to precede implicitly or explicitly the development of any curriculum, are:

- Which public is targeted? Is it only directed toward a minority or will every student be concerned?
- What is aimed at in the long term through this curriculum?

Answers to these questions are proposed in the different articles reviewed. In general, they can be found in introductions when authors highlight the relevance of their research. The justifications we encountered can be sorted out in two categories. The first one consists of pointing at the looming shortage of nanoscientists and nanotechnologists. Indeed some authors (Bryan et al., 2007; Stevens, Sutherland, & Krajcik, 2009a; Tomasik, Jin, Hamers, & Moore, 2009) reproduce discussions involving some of the NSF members that put forward figures assessing the number of nanoscientists that would be needed in 2015 (Roco, 2003). As a result, according to them, it is a matter of the US nation's interest to ensure that a sufficient number of nanoworkers be trained. To Foley and Hersam (2006), this need is made pressing for two reasons. First, the US is facing fierce competition in the field of nanoscale science and engineering research, in particular with Asian countries. In addition, the number of US students currently opting for STEM careers and their academic proficiency are both deemed insufficient. However, in articles dealing with secondary school nanoscience education, this argument rarely stands alone. It very often comes with the concern to give every student, irrespective of their future career, the opportunity to acquire a 'nanoscientific literacy'. Indeed, a second category of arguments draws the reader's attention to the omnipresence of nanotechnologies in our societies and assigns to school the duty to provide future citizens with tools to make informed decisions. Courses pursuing this second goal may differ somewhat from programmes principally aimed at training the future nano-workforce in nanoscience contents and practices. In this respect, considering the existing multiplicity of definitions of the expression 'Science Literacy' (Laugksch, 2000; Roberts, 2007), it seems to us legitimate to question the meaning of 'nano-literacy'. Some authors have also tackled this question and have proposed a first answer in a document entitled 'The Big Ideas of Nanoscale Science and Engineering' (Stevens et al., 2009a).

1.2. The 'Big Ideas' of nanoscale science and engineering

Convinced of the pressing necessity that nanosciences and nanotechnologies are included in school curricula, the NSF funded a series of workshops, which took place in 2006 and 2007. The book entitled 'The Big Ideas of Nanoscale Science and Engineering' published by the National Science Teacher Association synthesises the debates and conclusions of these working sessions. The expression 'Big Ideas' in this title designates fundamental concepts that would enable students to explain phenomena within and across disciplines.

These workshops had three intertwined goals:

> (1) to come to a consensus about what the "Big Ideas" were;
> (2) to address the challenges of bringing emerging nanoscale science and engineering into the classroom; [and]
> (3) to create a "consensus document" (this book) that could be used by educators, researchers and curriculum developers.' (Stevens et al., 2009a, p. 3)

Even though the authors lay emphasis on the intrinsic interdisciplinarity of nanosciences and nanotechnologies and insist on the necessity of preparing students to live in a society infiltrated by nanos, their definition of 'nanoscience and nanotechnology' remains vague, in our opinion. Indeed, they don't aim at sketching precisely the demarcations of these fields, but rather want to point to several core concepts that students will need either to act as informed citizens or even, for some of them, to develop the appropriate science and technology knowledge and skills to become part of the future 'nano-workforce'. They insist on their wish to have these cutting-edge notions taught not only in schools where traditional methods have been successful but also in schools where the proficiency level is lower.

In addition, to render those ideas coherent and to expedite their integration in classrooms, they aim at clarifying those key concepts (the 'Big Ideas') and at defining prior knowledge required to understand them – what students may be expected to know and be able to do according to their grade level. They also specify the articulation of these ideas with existing standards and benchmarks. Indeed, as the authors underlined, those national documents haven't so far made explicit the nano-related concepts to be taught, and without explicit links to the current standards, emerging scientific ideas are difficult to integrate into the curriculum. In this connection, they insist on the fact that nanosciences and nanotechnologies must not be considered as a single bulk unit but instead 'must' be integrated and related to traditional science concepts. To them, this may result in driving the curriculum to evolve towards more interdisciplinarity.

In order to reach those objectives, three workshops took place. The first one, held in June 2006, brought together 33 scientists and science educators. Their purposes were both to reach a consensus about 'big ideas of nanoscience' and to reflect on meaningful ways to incorporate them into the K-7 to K-12 science curriculum. A few months later, in August 2006, scientists and educators taking part in a second workshop, endeavoured to define the relevant 'big ideas' suitable for K-13 to K-16 students. The results of those two workshops were then addressed and scrutinised at the NCLT meeting in November 2006 where attendees worked to harmonise the two sets of 'big ideas'. Thus, at the end of this iterative cycle of meetings and brainstorming sessions, participants eventually agreed upon a set of 'big ideas' enriched by their associated prerequisite and learning goals, as well as indications about places where they could fit in the curriculum. Their conclusions were presented at a third NSF workshop, in January 2007. For 7th to 12th grade, a consensus was reached on the following nine core concepts:

- Size and Scale
- Structure of Matter
- Forces and Interactions
- Quantum Effects
- Size-Dependent Properties
- Self-Assembly
- Tools and Instrumentation
- Models and Simulations
- Science, Technology and Society.

These 'Big Ideas' seem to have encountered a rather large audience in the science education community, at least in the US. Indeed, different articles (Schank et al., 2007; Stevens, Delgado, & Krajcik, 2009) or abstracts that can be found in the 2007, 2008 and 2009 NARST Annual International Conference programmes all refer to them.

1.3. Taking advantage of nanoscience and nanotechnology to reform STEM education

Throughout the process of striking a consensus on 'Big Ideas', participants in the NSF workshops paid particular attention to three points:

- Taking into account the intrinsic interdisciplinarity of nanoscience itself.
- Dealing with the importance of complying with school system constraints – in particular with standards and benchmarks – to introduce those cutting-edge science concepts.
- Gathering an interdisciplinary team of scientists, educators and researchers to design appropriate curricula including nanoscience, appropriate to the secondary school level and equipment without overlooking significant scientific aspects.

As we will point out later, these three points are of particular importance in designing relevant curricula, and developing nanoscience pedagogical resources or assessments. Regarding interdisciplinarity and standards, some authors even go one step further. For example, Schank et al. (2007) plead for nanoscience to constitute a catalyst bringing about a fundamental reform of an ailing US STEM educational system shaken by the TIMSS (Trends in International Mathematics and Science Studies) low scores obtained by US high school students. In this respect, they echo previous calls for radically modernising the science curriculum, for instance by Hurd (2002). Indeed, to them, nanoscale science and technology demand that standards be updated and partitions between traditional disciplines knocked down to eventually promote real interdisciplinary teaching matching modern science reality.

1.4. Summary and discussion

Among the reflections prior to the design and implementation of a curriculum including nanosciences and nanotechnologies components, we identified five questions:

- What is aimed at through the introduction of nanosciences and nanotechnologies in secondary school?
- Who will participate in these new programmes?
- What concepts are considered as essential to grasp some understanding of the heterogeneous objects of research of nanotechnologies?
- How can these 'nano-components' be integrated in the curriculum?
- To what extent can nanosciences and nanotechnologies be regarded as an opportunity to reform STEM education?

Two main goals are often assigned to the introduction of 'nanos' in secondary school. First, the economic stakes are said to be enormous and consequently some consider secondary school has to adapt to prepare future 'nanoworkers'. In addition, if nanosciences and nanotechnologies pervade society, future citizens will be confronted with debates involving these emerging sciences and technologies. As a result secondary school should prepare every citizen to understand and participate in these debates by making them acquire a 'nano-literacy'.

In addition, nine 'Big Ideas' fundamental to building this student nano-literacy have been identified. These key concepts have been related to current US Standards to help teachers integrate them in their lessons.

Questioning the goals of introducing nanosciences and nanotechnologies appears to us as crucial. Given that: the development of nanosciences and nanotechnologies is controversial; governments have invested a colossal amount of money to remain at the forefront of nanometric scale innovation; and nanotechnologies are often presented, particularly in France, as some sociologists have underlined (Joly et al., 2005), as a direction that has to be inescapably followed by decision-makers without discussing the legitimacy of this assertion, then society and in particular science educators should be alert to developments. Pressures may be exerted to turn lessons on nanosciences and nanotechnologies into opportunities to promote the 'acceptability of these technologies'. However, as we outlined earlier, the authors of many studies also argued that the introduction of nanosciences and nanotechnologies in secondary education should contribute to the acquisition of a 'nanoscientific-literacy'. We side with this position. Indeed, to us, as far as secondary school is concerned, nanosciences and nanotechnologies lessons should be designed so as to provide students with tools to act as informed citizens. Modules on controversial topics such as nanosciences and nanotechnologies should help foster students' critical thinking so that they can understand and participate in such debates. Consequently, the controversial aspects of nanosciences and nanotechnologies should by no means be played down.

Furthermore, the answers to the question 'what concepts are considered as essential to grasp some understanding of nanosciences and nanotechnologies?' suggested by the identification of 'Big Ideas' display a mix of new ideas such as self-assembling, alongside elements that are by no means exclusively referring to nanosciences and nanotechnologies (dominant forces, size and scale etc.). Consequently, this choice of essential concepts makes nanosciences and nanotechnologies appear as an opportunity to reconsider already existing contents that may have been taught for decades. We can draw here a parallel with what happens in scientific research. The allegation is sometimes put forward that many scientists choose to re-label their studies 'nano' to benefit from funding allotted to this strategic field (Joly et al., 2005). Here, in science education, concepts might be relabelled 'nanos' to seize the opportunity to emphasise them in curricula. This could be the case for size and scale, especially as this idea is considered important by different science educators – as will be developed further, in section 2.1 – and as these notions are not taught in the context of a particular discipline of the traditional curriculum.

Nanosciences and nanotechnologies can be thus considered as an opportunity to rethink STEM curricula, not only contents but also pedagogy. This point will be also underlined further, in section 4.2.

As this review demonstrates, different directions have been pointed out to develop appropriate curricula, in particular thanks to the inventory of 'Big Ideas'. Nonetheless, these reflections presently need empirical research to produce more informed decisions about how to design and sequence relevant science curricula. We now turn our attention to empirical studies on nano-related conceptions.

2. Studies dealing with students' nanoscale science and technology related conceptions

This part of the review is limited to research in science education about conceptions of size and scale, size dependent properties and of the nature of matter for various reasons. First, these were the three topics we encountered in the articles that we gathered at first and selected for our review. Then, the definition of nanoscience and nanotechnology remains vague. To avoid confronting the thorny problem of definition, we deliberately chose to delve only into articles stating explicitly their interest in nanoscale science and engineering education. This bias has consequences: for instance, articles about conceptions on chemical bonding remain absent in this review.

2.1. Size and scale

The authors of the articles mentioned in this section emphasise the lack of research investigating how students conceptualise different sizes and spatial scales. They consider this deficit all the more blatant as 'size and scale' has been recognised as one of the unifying themes useful for making connections between different disciplines by the American Association for the Advancement of Science in 1993 (AAAS, 1993).

Research on students' existing conceptualisation of scale

This research by Tretter, Jones, Andre, Negishi, and Minogue (2006a) explores the students' conceptualisation of scale. Accordingly, they try to determine the cognitive frameworks concerning conceptualisations of size and scale and detect a potential variability as a function of age. They also seek to understand the possible influence of formal educational and other experiences and finally compare students' conceptualisations of scale with those of 'experts' in science. 215 students were involved. They were divided into five groups: 5th, 7th and 9th grade students from a single school district, 12th grade 'gifted' students and a few doctoral students. Three types of data were collected. First, participants had to rank 31 elements by order of size. Then, they had to sort cards displaying pictures of objects by collecting together those which had similar sizes. Finally, they answered interviews where they explained their sorting and were asked about previous experiences that helped them to learn about size and scale. The researchers analysed these data by considering each group as a single entity. They computed absolute rankings for each group and by taking into account the relative positions selected by each participant they obtained relative rankings. The analysis of these rankings enabled them to identify conceptual boundaries of distinctly different sizes. It appeared that 12th grade and doctoral students (referred to as 'experts') distinguished more refined categories for small size objects. From interviews, the authors also picked out significant size landmarks used by participants to conceptualise different scales and argued for the importance of past direct (holistic or sequential, visual or kinaesthetic) and indirect experience, to build size and scale knowledge. This significance of past experience in cognition development was reasserted with multidimensional scaling analysis of the card data sort. As a result, in their discussion, the authors suggest that resorting to virtual reality tools could prove a beneficial opportunity to provide students with those much-needed direct experiences. In this respect, it seems to us worth noting that some of these authors investigated the influence of using one of these tools, named ‘NanoManipulator’. This research will be discussed later. Finally, the interviews with ‘experts’ gave some insights into their strategy to conceptualise extreme scales. In particular, they seem to have developed a capacity to ‘unitise’. To put it differently, they introduce new units that are, to them, more adapted to a particular scale.

Accuracy of students’ scale conceptions

In another paper, Tretter, Jones, and Minogue (2006b), attempt to determine the accuracy of scale conceptions held by students and the strategies used to improve this accuracy. The groups of students participating in this study were the same as in the previous work. To meet their research objectives, the authors used both written assessments and interviews. Data analysis tended to reveal an asymmetry between small and big scale conceptions. Concerning scales comparable to the size of human body, conceptions held by each group were very accurate. As for accuracy relative to large-scale conceptions, it smoothly declines as scale increases. On the contrary, small-scale accuracy slumps abruptly at the microscopic level for each group. To these authors, this discontinuity indicates that there exists difficulty in mentally manoeuvring beyond this threshold of non-visibility. Furthermore, the accuracy of scale conceptions of the youngest group spans over a narrower spatial interval compared with other groups. In addition ‘experts’’ conceptions at the nanoscale appear to be more accurate than their microscale conceptions. Apart from this latter category, participants tended to overestimate big sizes and underestimate small ones.

This difficulty in apprehending small scales, especially objects invisible to the naked eye bolsters the results presented in the article previously discussed (Tretter et al., 2006a). Concerning strategies developed by experts to conceptualise extreme scales, the findings presented in this article allude to a ‘mental jump’ across spatial scales in a ‘different world’. This ‘world’ is often characterised by the reference to a particular tool (electronic microscope, AFM etc.) or to a particular unit for that scale. This kind of strategy has already been pointed out in the previous research where it was referred to by the word ‘unitising’. This last result is not really surprising since both articles deal with one unique sample. They may even rely on the same data interviews to draw this same conclusion.

How are size and scale related concepts connected?

Delgado, Stevens, Shin, Yunker, and Krajcik, for their part, presented at the 2007 NARST conference, research aimed at gaining knowledge on how students develop their conceptions of size and scale. This conference was held a few months after the NSF workshops on the ‘Big Ideas’ of Nanoscience for which four of these authors were part of the organising committee. These authors endeavour to determine whether, how and when students build connections between four size-related aspects: ordering; grouping; number of times bigger an object is relative to another object; and absolute size. They also seek a potential variability with respect to ethnicity or gender[1] and plan to use their findings to build a learning progression. As Stevens et al. remind us in a subsequent article (2009b), there is no consensus on the definition of learning progressions nor how they should be developed. To them, a learning progression describes how students can build a more sophisticated knowledge of a ‘big idea’, a subject pervading science, over a large span of time. By their very nature, such learning progressions remain hypothetical. In this research on size and scale, Delgado et al. study a total of 42 pupils of 7th to 11th grade from a small industrial town in the Midwest as well as six undergraduates from Midwestern University. Individual tape-recorded interviews were carried out where students were asked:

- to arrange by size 10 cards depicting objects of different sizes, from virus to planet;
- to group the cards by size;
- to determine for five cards correctly ranked, how many times bigger an object was relative to another one; and
- to venture an hypothesis on the absolute size of five objects.

Conceptual connections were investigated. Consistency between answers was taken into account to code the data. The authors found that the most frequent connection linked ordering and grouping (83% of participants), followed by ordering and number of times bigger (75% of the cross-section). In addition, 64% of students succeeded in answering consistently in ordering and estimating the absolute size tests. About two thirds of the participants did not perceive the logical and necessary connection between the absolute size of two objects and the multiplicative factor linking their dimensions and only 13% of them answered consistently on those two tests. From these results, the authors generated a first model of a learning progression. In addition, if students' ethnicity, gender and grade did not appear to be correlated to their answers, their academic achievement and the science class the student was attending, seemed to have statistically an influence. Finally, the authors underline that it went beyond the scope of the research to explore the influence of knowledge in establishing connections (for instance: a mitochondria is inside a cell and consequently must be smaller than a cell), but that research in that direction would be welcome.

It would be rather awkward to compare the findings of this latter research with the earlier projects reviewed. Indeed, these authors focus on connections between different aspects useful to conceptualise scales rather than on particular difficulties that students may encounter in this conceptualisation. Moreover, they do not investigate which strategy can be used to develop these connections even though they call for research in this direction by pointing out the potential influence of knowledge on their establishment. In particular, they do not question the significance of direct experience. In this connection, research by Jones and Taylor (2009b), relying on semi-structured interviews of 50 professionals has been conducted to document how understanding of scale develops from childhood to adulthood. The results tend to indicate that among the cross-section under study consisting of persons likely to use scales in their works, the majority of participants considered the role played by scale in their work as prominent and resorted to anchor points to move across different scales. Seventy-six per cent of participants also alluded to physical experiences as elements involved in their developing a sense of scale.

Finally, in identifying the difficulties of conceptualising size and scale, the first two articles presented in this section plead for enhancing these aspects in secondary school. The third one, for its part, suggests a learning progression that may inform curriculum developers. However, their findings seem to reveal that the building of these connections is not correlated to grade. The decision relative to where this learning progression would fit in the curriculum thus remains pending.

In order to map the current research carried out in the field of nanosciences and nanotechnologies onto secondary education, we now turn to another research topic: conceptions relative to the particulate nature of matter.

2.2. Nature of matter

Stevens et al. (2009b) pursue the similar goal of building a learning progression about the 'nature of matter' in another NSF supported research project. Using an iterative design-based research method, they aim at describing how students build models for atomic structure and for the electrical forces governing molecular interactions at different scales, as well as how they establish connections to organise their knowledge. Building upon a learning progression previously developed by Smith, Wiser, Anderson, and Krajcik (2006) for K-8 students, they offer a hypothetical learning progression they have empirically tested in order to further refine it.

They resorted to a 'constructed-centred design' process. The two constructs they were investigating, were the atomic model and electrical forces. Accordingly, they identified a set of crucial concepts for understanding the content of these constructs as well as relevant phenomena to illustrate them. Then, they targeted what students could be expected to be able to do with the knowledge ('claims') and the behaviours and performances associated with it ('evidence'). Finally, they designed a related question to test this ('task').

Their empirical work involved 30-minute semi-structured individual interviews, conducted with 37 middle and high school students attending a public school, 31 students from a private school and five undergraduates (both science and non-science majors) from Midwestern University having completed at least one year of high school chemistry. From these data, multidimensional empirical learning progressions on atomic structure and electrical forces were designed and compared with their hypothetical learning progressions. To put it roughly, the hypothetical learning progression (HLP) for atomic structure consists of four main levels:

- atoms as spheres;
- atoms composed of charges;
- different models for atoms: a. Bohr model, b. Electron cloud model; and
- energy levels and Pauli principle.

As for the HLP for electrical forces, it is made of five main levels:

- unspecified force governs interactions;
- mechanisms specified (attractions, repulsions);
- interactions governed by electrical forces;
- continuum of electrical forces; and
- importance of the environment.

They also enhanced the relationships between these two learning progressions and built a multidimensional HLP. Their empirical results for atomic structure revealed that 69 of 73 students fit the learning progression for atomic structure. Over 80% of grade 7–14 students had a model for an atom and 28% still only represent an atom as a sphere. Besides, the results tend to show that the majority of students interviewed were presently at level three of four in their development of an understanding of electrical forces.

Then, relying on these learning progressions confronted with previous research results, Stevens et al. (2009b) discuss instructional strategies that could favour connections between concepts. To its authors, this research supports the conclusion that it is unproductive to introduce too much detail of atomic structure too early. Indeed, to them, new knowledge has to be made meaningful to be properly integrated by students. As a result, students should be introduced to new information only when a need has been created to explain a phenomenon or a concept. Here, these authors specify that the introduction of the periodic table may foster the need for students to develop a model for atomic structure. In addition, throughout their discussion, they repeatedly stress the importance of models, of making students aware of their limitations and of the importance of discussing the reasons that lead scientists to introduce and utilise different ones. Finally, they lay emphasis on the significance of helping students to make connections so that they gain an integrated knowledge structure. To them, this importance is reinforced by the interdisciplinary nature of nanoscale science. It thus requires a new approach to developing instructional material that is, in their opinion, currently designed following a disjointed approach.

2.3. Size dependent properties

Another aspect related to a 'Big Idea' identified during the NSF workshops has also been recently investigated. Taylor and Jones (2009) have carried out a study dealing with size-dependent properties. In an exploratory study, they try to determine if there is a correlation between proportional reasoning ability and understanding surface area to volume relationships (Taylor & Jones, 2009). This latter aspect plays a prominent role in explaining the behaviour of some nano-objects. However, Taylor and Jones assert that is not clear yet, where this aspect of scale should lie in the K-12 curriculum. Accordingly they seek to gain knowledge on a 'developmental basis' for understanding scale.

This study involved 19 students from 11 to 13 years old taking part in a five day summer camp. Students' proportional reasoning skills were assessed by means of an instrument previously developed consisting of 10 open-ended questions. In addition, an instrument aimed at probing students' understanding of surface area to volume relationships was developed. It comprised a pre- and a post-test. Each of these tests consisted of answering multiple choice questions, problem-solving items, filling diagrams, and giving explanations for some answers.

According to its authors, the results of this study revealed a significant correlation between proportional reasoning ability and achievement in the test on surface area to volume relationships.

In their discussion, the authors then asked three questions:

> What developmental level is necessary for students to understand fully the relationship between surface area and volume? What type of background knowledge is necessary for students to understand surface area to volume relationships and how does it affect the sequence of science instruction? What other constructs (such as visual spatial skills) may be involved in understanding of scale applications such as limits to size and surface area to volume relationships? (Taylor & Jones, 2009, p. 1237)

The first two questions seem to us to echo the preoccupations of Delgado et al. (2007) and Stevens et al. (2009b) as they try to identify hypothetical learning progressions.

Considering the results of this exploratory study, Taylor and Jones assert that, if further findings should reveal that students need to reach a critical level of proportional reasoning ability in order to be able to grasp surface area to volume relationships, then, reordering science curricula may prove necessary. In this respect, they emphasise the fact that making more connections between mathematics and science may be fruitful.

2.4. Summary and discussion

Studies on students' conceptions presented here emphasise both how students conceptualise diverse nano-related concepts (size and scale, size dependent properties, atomic structure and electrical interactions) and how they make connections between notions. They focus on cognitive development. Some research concerning size and scale tends to reveal that students encounter difficulties in apprehending extreme scales, in particular small scales, and hint at the fact that direct experiences play an important role in their conceptualisation (Tretter et al., 2006a; Tretter et al., 2006b). As a result, since nanometric scale is not directly accessible to direct sensory experiment, it emphasises for us, the role that tools and instrumentation can play in building an understanding of this scale.

Hypothetical learning progressions on size and scale and on atomic structure and electrical forces are also developed and empirically tested to propose a relevant instructional strategy and help students building connections between concepts (Delgado et al., 2006; Stevens et al., 2009b). In their work on atomic structure and electrical forces, the authors stress the importance of meaningfully introducing models and of making students aware of their limitations. Models along with simulations have also been identified as a 'Big Idea' of Nanoscale Science and Engineering (Stevens et al., 2009a).

Finally, the study on size-dependent properties investigates the link between proportional reasoning and the comprehension of surface area to volume relationships (Taylor & Jones, 2009). This last concept is indeed of central importance to understand some particular properties of nanomaterials. The authors found a significant correlation between the results of tests on these two concepts. Consequently, they call for further investigation to be carried out, because to them other results showing such a correlation may lead to a reordering of the science curriculum.

In fact, in these articles, the exploration of the understanding of concepts that are not specific to nanosciences and nanotechnologies but deemed central to build a comprehension of nanoscale phenomena, comes along with a demand to reconsider the existing curriculum for secondary school by insisting more heavily on some particular aspects or by re-sequencing them. These calls for reviewing the US secondary school curriculum can be compared with the proposal by some researchers previously reported (Schank et al., 2007) to take advantage of nanosciences and nanotechnologies to profoundly modernise STEM education and promote connections between disciplines.

As research is undertaken to understand how students conceptualise different concepts, studies have been carried out on particular pedagogical materials used to teach them. For example, concerning size and scales, Jones et al. (2007a), investigated the influence of the film *Powers of Ten*. Even though it was produced about 40 years ago, US teachers still frequently use it to approach spatial scales, according to these authors.

Though some already existing pedagogical tools can be useful in teaching nano-centred lessons, other more recent materials have also been designed. We now present some of those we encountered in the articles collected for this review.

3. Learning tools: AFM coupled to a haptic device

The prominent role played by instrumentation in the development of nanoscale sciences and technologies was stressed during the 2006 NSF's workshops as tools were recognised as a 'Big Idea'. Indeed, as many authors put it, and as underlined in the National Nanotechnology Initiative 2007's strategic plan, the possibility to observe and manipulate nano-sized objects constitutes a decisive step towards the development of nanosciences and nanotechnologies (NNI, 2007; Schank et al., 2007; Vinck, 2009). As a result, the presentation or use of these brand-new tools, particularly AFMs, are often allotted a prominent place in university nano-centred courses or in instructional sequences about nanoscale sciences in secondary schools.

However, a major inconvenience of these cutting-edge devices is their prohibitive cost. They are not affordable for many schools (Madden et al., 2007). Accordingly, different solutions have been proposed to get round this problem. Different articles published in *Physics Education* and in the *European Journal of Physics* display cheap home made models of AFMs that can be used at school (Greczylo & Debowska, 2006; Planinsic & Kovac, 2008; Zypman & Guerra-Vela, 2001). Yet, even if we haven't found throughout our literature review any scientific article focussing exclusively on the influence of these particular AFM models on pupils' learning, the literature does contain studies of instructional sequences using AFMs. In the following section, we will first throw light on research about a device coupling an AFM to a haptic interface[2]. Then, we will vet an article investigating the influence of haptic interfaces used with a simulation combining biology and the use of an AFM, on students' learning and motivation.

3.1. Impact of using an AFM coupled to a haptic interface on students' engagement and learning

AFMs are at the heart of a programme about viruses for high school students designed by science educators of the University of North Carolina. Researchers of this university have indeed developed a 'nanoManipulator' coupling an AFM to a haptic interface rendering possible the sense of touch and allowing both tactile and kinaesthetic experience. A virus under study is located at the University of North Carolina. Students remain at school where they use the nanomanipulator and are able to manipulate and feel the virus by controlling the tip of the AFM through the Internet. In addition, they are able to visualise in three-dimensions the probed object thanks to the nanoManipulator software. Although this is barely mentioned by the authors of these articles, this instructional sequence constitutes an interdisciplinary approach of nanoscale sciences intertwining at least biology and physics.

This device has been under study in different articles (Jones, Andre, Superfine, & Taylor, 2003; Jones et al., 2004). We will review these papers, and then examine the results of research questioning the influence of haptic tools on learning and motivation (Jones, Minogue, Tretter, Negishi, & Taylor, 2006).

Exploratory study

Through a preliminary study, Jones et al. (2003) analysed this experiment from two different angles. They investigated how a weeklong educational experience affected students' learning and sought to understand how the absence of haptic feedback may impact on students' conceptions of viruses. The cross-section of participating students included 24 boys and 26 girls, from two different North Carolina biology classes whose teachers were interested in introducing nanos in their classroom. There were 21 students of 10th grade, 25 of 9th grade and four of 11th grade. Different activities were organised during the week. On the first day, the whole class attended a session given by a scientist dealing with size and scales, different types of microscopes and the nanoManipulator they were about to use. For the next three days, the classes were divided into small groups of four to five students and each group went through six 'working stations' consisting of: using the nanoManipulator; using a macroscopic mechanical model of an AFM; interviewing scientists (two 'working stations'); and writing an article about this one-week instructional experience (also two 'working stations'). Every activity was designed to last about 20 minutes.

In order to obtain information on the impact of haptic experiments, researchers planned that one of the class, randomly selected, would handle the nanoManipulator without tactile feedback. However, as the AFM's tip proved impossible to control under these conditions, they had to make do with setting up the machine so that it rendered only 'limited-haptic feedback'.

To answer their research questions, they used an instrument previously tested (Jones, Superfine, & Taylor, 1999) and structured around pre and post knowledge tests, 12 pre- and post-interviews, pre and post opinion questionnaires about this instructional sequence, as well as questionnaires about how it may have influenced the way students consider science. During these interviews, students were asked to model clay adenoviruses, which were also included in the data, along with the students' newspaper stories. From meticulous analysis of these data, Jones et al. (2003) draw the following conclusions:

- This instructional week had a positive effect on students' knowledge of viruses, nanoscale and different types of microscopes. In particular, many of them moved from a plane to a three-dimensional representation of viruses.
- Concerning the influence of haptic feedback, no significant discrepancy between the two groups appeared in the results.

The authors hypothesise this latter result could be explained by the small size of the cross-section or by the assessment which did not enable direct investigation of the influence of the haptic device. Consequently, they suggested that further research is needed.

Study on a larger scale and more precisely focused on the influence of haptic experiences

This weeklong educational experience that seems, according to Jones et al. (2003), to have been successful with the majority of participants, was repeated a few months later on a larger scale (Jones et al., 2004). In the meantime, the schedule for the instructional week underwent slight changes. During the second day of instruction, they were taught about scale in three 15-minute activities including training on how to use the nanomanipulator, comparing their size to the size of a toy, and watching the video 'Powers of Ten'. In addition, one of the writing activities of the six working stations was replaced by an activity on spatial scales. On the other hand, the methodology seems similar to the one mobilised for the exploratory study. Two hundred and nine students took part in the experiment. They came from two different grade levels (7th grade and high school), in order to test possible variability in the efficiency of using the nanoManipulator contingent with grade level.

This time, the research team more precisely focused on the influence of haptic experience and strove to answer three research questions:

- How do haptic experiences influence students' concepts of viruses?
- Do haptic experiences with nanosized objects change students' understanding 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? (Jones et al., 2004, p. 58)

Once again they split the cross-section into two groups. The first one used the nanoManipulator with full haptic feedback, whereas the other one received a limited haptic feedback[3]. The analysis of this experiment mainly shows converging results with those previously found in the exploratory story, with one noticeable exception.

On the whole and irrespective of their exposure to haptic feedback, students showed more positive attitudes after this instruction towards science, towards the idea of performing experiments with microscopes and to do science for a living. In addition, they more deeply understood scale, AFMs and knew more about viruses. Furthermore, the authors claim that, to them, the students who experienced the full-haptic device feedback showed significantly better attitudes than the others. Yet, they don't discuss this result by contrasting it with the exploratory study where no significant difference was found between the group receiving full haptic feedback and the other one. The authors only call for further research to check if the influence of haptic experiences on the student's attitude is noticeable across different types of experimentation and suggest investigating the use of haptic devices for students with visual disabilities[4].

Apparently, these instructional weeks on nanosciences have been repeated for pupils. This approach was indeed studied, following a different approach a few years later (Jones et al., 2007b). This time, the research focused on the potential influence of ethnicity on students' attitudes toward this nanoscale sequence and on the perception participants had of their engagement in this activity. To reach these aims, Jones et al. (2007b) analysed pre and post opinion questionnaires and thoroughly examined the newspapers stories written by participants. We won't give here a detailed account of the results obtained during this research since the viewpoint adopted to consider the problem goes beyond the limits of our work. However, we thought it worth mentioning as it echoes a concern already encountered in this article: will a particular device have a different impact depending on ethnicity? In our opinion, at least two reasons can justify the interest of science education research in this question. Our first explanation is that according to many discourses, nanosciences (as well as sciences in general) should, as a rule, be made accessible to any pupil, irrespective of gender or ethnicity. The second justification is that, according to many authors, it is a matter of one nation's interest, to ensure that enough students pursue STEM careers. Since many nanoworkers will be needed, students from minorities should also be encouraged to study nanosciences.

3.2. Influence of the haptic interface quality in AFM experiments

To enrich reflections about haptic interfaces, the same research team compared the effect of using different interfaces instead of a simple mouse (Jones et al., 2006). Two haptic tools are here examined: one referred to as 'PHANToM' previously used with the nanoManipulator and a cheaper joystick developed by the gaming industry. Indeed, as the authors of this article emphasised, the cost and logistics of implementing that kind of instructional activity limits the possibility of widely extending this type of nanoscience teaching. 'PHANToM' simulates the sense of touch thanks to its six-degrees of freedom and by sending the forces of interaction directly to the fingertips of the user. On the other hand, the joystick has two-degrees of freedom and communicates forces with a much lower quality. The comparison takes place in the context of a computer-mediated inquiry activity called 'Investigating Viruses: The Mysteries of the Sick Puppy.' During this module, students play the role of scientists who try to diagnose by means of several experiments, which virus has infected a dog. In particular, they resort to AFM microscopy.

This work aims at investigating the influence of the interface on both learning and attitudes developed by students toward this instructional device. Thirty-six middle and high school students experienced working with this device for this study. All pupils work in groups of two and six of these groups were observed as they worked with the programme, and their verbal exchanges were recorded in full. In addition, at the end of this instructional session, every student completed a questionnaire to probe their knowledge on viruses and their attitudes toward this instruction.

The data analysis disclosed, according to the authors, that students working with haptic interfaces engaged more deeply with this activity than those working with a mouse. Significant differences also appeared in the number of viruses' characteristics that students remembered after working on this activity, as well as in the interest they found in working with an AFM. Researchers also noted, by means of discourse analysis, that students allowed to run the programme with haptic tools used affective terms more frequently or alluded more readily to tactile feelings. In addition, the more sophisticated the interface, the more marked were these trends. The authors of this article interpret those data by asserting that the haptic feedback may influence the nature of learning and might affect its cognitive outcomes. Thus, these results seem to corroborate the previous research results. Nonetheless, the authors of the study, being aware of the small cross-section taking part in this experiment, once again call for further research of the same type to be carried out.

3.3. Summary and discussion

The three studies reviewed here take interest in the use of haptic tools rendering the sense of touch coupled to an AFM or with a simulation of AFM microscopy to learn some nanosciences and nanotechnologies related concepts. The studies examined here tend to agree on the positive impact of using haptic interfaces coupled with an AFM on both students' learning and engagement in the activity (Jones et al., 2006; Jones et al., 2004; Jones et al., 2003). Yet, they demand further research on these kinds of devices. So far, the results seem to indicate that the more sensitive the haptic tool is, the more efficient it is (Jones et al., 2006) in engaging students and supporting learning.

The advent and development of near field microscopy (including AFM) has prompted the availability of nanoscale pictures. Consequently, the productions of scientists working in the field of near field microscopy are often used as illustrations of 'nanos' even though much nanotechnology work does not resort to these techniques and tools. As a result, the introduction of atomic force microscopy in nanosciences and nanotechnologies' teaching, is in our opinion, not surprising.

In addition, the studies presented here seem to indicate that the AFM coupled to the use of visualisation and haptic tools may offer a meaningful approach to dealing with some size and scale concepts. As some people call for nanosciences and nanotechnologies to 'catalyse' a STEM education renewal (Schank et al., 2007), their introduction in secondary school may also be regarded as an opportunity to test innovative learning tools.

Furthermore, as visualisation enabled by the AFM is a spatial reconstruction of force information, the capacity of haptic tools directly to convey these forces may be used to understand how the AFM tip interacts with a surface or an object. If dominant forces and interactions are considered as central concepts to be taught to understand some nanoscale phenomena, haptic tools may directly help students to build an understanding of these notions. However, this particular aspect of haptic utilisation is not investigated in the studies reviewed here.

In addition, in the studies of the one-week educational experiences offered to high school students, the impact on students' attitudes after this instruction towards science or even towards the idea to make science for a living appears positive overall. In a context where some studies point to the looming shortage of nanoscientists (Foley & Hersam, 2006), some activities may be designed to entice students to engage in science for a living and show science in a pleasant and appealing way. However, even if the job prospects are claimed to be huge (Foley & Hersam, 2006) and even if money may be allotted to nanoeducation programmes partly to provide society with enough nanoscientists or nanotechnologists to remain at the forefront of research, we reassert the importance of designing lessons on nanosciences and nanotechnologies which do not conceal their more controversial aspects.

Moreover, although these haptic tools seem to have had a positive impact on students' understanding of scale, AFM and viruses, owing to the high price of these devices, every school cannot afford to purchase this equipment, at least not in the short term. Thus only a small number of students will benefit from using them. Consequently, if the purpose of introducing nanos to schools is to form a nano-literate population, other strategies and other tools also need developing.

However fruitful this experience may be for students, to make nanos permeate the secondary science curriculum, teachers have sooner or later to be in charge of teaching these new contents. This raises the question of their professional development.

4. Secondary teachers' professional development

One of the hurdles hampering the introduction of nanosciences and nanotechnologies by teachers in the classroom is the inadequacy of their professional development. (Schank et al., 2007; Healy, 2009). Although many pedagogical resources are already currently available, especially on the Internet – for example on the NCLT's NanoEd Resource Portal Website, the Case University's Nanopedia Project and the Stanford

Research Institute (SRI) International's NanoSense project webpages – many difficulties need overcoming to enable teachers to incorporate nanos in their lessons.

4.1. Problems entailed by the introduction of emerging science into classrooms

As outlined earlier, there exists at the present time, a wide consensus on the necessity to promote interdisciplinarity in teaching nanosciences. However, science courses seldom escape the partition between traditional science disciplines. In addition, as Schank et al. (2007) remind us, teachers have often majored in one discipline. Therefore, they may not feel at ease when it comes to including in their lessons topics from other disciplines. This reluctance to deal with subjects from a discipline they have not been acquainted with may be reinforced by their lack of content knowledge in this emerging and evolving field (Schank et al., 2007). Indeed, teachers may lack the opportunity to keep abreast of new scientific developments (Tomasik et al., 2009).

Accordingly, to avoid teachers becoming deterred from bringing nanos into school for fear they should find themselves at a loss in answering pupils' questions, or detecting and acting on students' difficulties, different authors have put forward different propositions. To address the question of pre-service teachers' professional development, some point to the short term solution of organising science method courses dealing with interdisciplinary and cutting-edge topics including nanoscale sciences and technologies (Schank et al., 2007). In addition, to provide teachers with thorough explanations of phenomena and approaches to guiding discussions, these authors suggest educational material should be created. They also underline that some summer schools for teachers are already proposed by the NCLT. We will return to these particular professional developments initiatives later in this section. Indeed, some of these courses for teachers are currently being investigated and research has already produced some results.

4.2. Empirical work on teacher professional development courses on nanotechnologies

An on-line nanoscience course

Researchers from the chemistry department of the University of Wisconsin-Madison describe in an article published in the *Journal of Nano Education* the design and evaluation of an online nanoscience course for middle and high school teachers (Tomasik et al., 2009). During summer 2006, 13 participants volunteered to enrol in an eight-week course to gain knowledge on nanoscience and nanotechnology and to obtain different resources to include nanos in their classrooms. The 'foremost goal' of the authors of this article is reportedly to encourage teachers to incorporate nanosciences and nanotechnologies in classrooms because, to the developers of this course:

> Training the next generation of nanoworkers is a primary challenge for furthering nanoscience advancement. (Tomasik et al., 2009, p. 48)

Taking into consideration research results, they used a freeware to create a collaborative online environment enabling teachers to interact with their peers and their instructors. The evaluation surveyed the gain in knowledge and the online learning environment. Before the beginning of the course, participants completed a questionnaire to assess their knowledge about nanoscience and nanotechnology. Every Monday, a new topic was introduced and once it was completed, participating teachers had to answer an online questionnaire. These data were used to estimate whether learning goals had been attained. Eventually, at the end of this professional development programme, participants had to build their own nanoscience module that could possibly be taught in front of pupils. These modules were then anonymously peer-assessed by two other participants.

The results were rather positive, according to the authors of the article. Indeed, the quality of teachers' answers on content knowledge questions improved a lot between pre and post-tests. Furthermore, an evaluation of the collaborative online environment was performed. They used a tool named 'COLLES' (standing for Constructivist On-Line Learning Environment Survey) taking into account six dimensions: professional relevance, reflective thinking, interactivity, tutor support, peer support and interpretation of meaning (in other words, do students and instructors understand each other when they communicate by using the on-line environment). According to the article, results concerning professional relevance and tutor support were very good. However, those relating to interactivity and peer support still have a margin for improvement. Concerning the proposition of lessons produced by teachers, two different schemes could be distinguished. The first one consists of disseminating lessons on nano-related topics at different times of the year whilst the other strategy involves building one complete unit that will be given once in the school year.

Eventually, one year after following this course, participants were asked whether they had implemented nanolessons in front of their students. It appeared that of 10 teachers who responded, eight had taught their modules in their classroom. Unfortunately, the reasons motivating their decisions to include nanos (or not to) in the science curricula are not made explicit. Nevertheless, this seems to indicate that this professional development intervention resulted in the introduction of nanosciences into a few secondary classrooms. Yet, even if all the teachers volunteered and were thus disposed to introduce this emerging science into their lessons, every participant didn't integrate nanolessons the following year. This once again underlines the difficulties of effectively integrating nanos into curricula.

Other professional developments are currently available for teachers. In particular, the National Centre for Learning and Teaching (NCLT) organises a programme in order to help secondary teachers to integrate 'nanoscale science and engineering' into the science curriculum. This programme was and is still scrutinised by a science education research team from Purdue University.

A designed-based approach to teachers' professional development

In this section we have used paper proceedings presented at the NARST 2007 annual meeting (Bryan et al., 2007) and also draw on 2007 and 2009 Proceedings from the American Society for Engineering Education (Daly & Bryan, 2007; Daly, Hutchinson, & Bryan, 2007; Hutchinson, Bryan, & Bodner, 2009). It is worth underlining that the design-based research projects which we are referring to, are still in progress and were discussed during both NARST 2008 and 2009 conferences. The papers we reviewed, deal with one of the initiatives of the NSF funded NCLT, directed toward teachers. This programme consisted mainly of: a summer school where teachers attend lessons on nanoscience concepts; seminars by nanoresearchers during the following school year; and the implementation of inquiry-based lessons including nanoscience.

The authors report two types of purposes for holding these workshops. First, they aim at enhancing secondary teachers' understandings of nanoscale phenomena and awareness of connections between nanoscale science and technology, and traditional disciplines. Secondly, they pursue pedagogical purposes by trying to promote reflections on inquiry-based science teaching and learning, and by providing teachers with enhanced knowledge and skills for implementing inquiry-based methods. To reach these goals, they intend both to examine teachers' development of professional knowledge and to design effective professional development for secondary teachers in nanoscale science. Accordingly, they chose a design-based approach and planned to iteratively alter this professional development by taking into account their research results. In the papers referring to the first workshop session held in 2006, the research questions the authors addressed are the following:

- What are the teachers' conceptions of nanoscale science?
- What are teachers' conceptions of inquiry?
- How do teachers design inquiry-based nanoscale science instruction?
- What prerequisite knowledge and skills are needed to teach nanoscience concept?
- How do the 'Big Ideas' in nanoscale science that we taught align with existing local and national standards? (Bryan et al., 2007, p. 12)

The workshops were framed around five major themes: size and scale, structure of matter, properties of matter, fabrication, and tools. These themes thus overlap with some of the 'Big Ideas of Nanoscience'[5]. In addition, particular attention was given to teachers' conceptions of models and modelling as related in the 2007 ASEE (American Society for Engineering Education) proceedings (Daly & Brian, 2007).

The summer workshop was consistent with Indiana's current standards and designed to implement inquiry-based methods and pedagogical discussions. All 12 participating teachers voluntarily applied to it.

To answer the research questions, different types of data were gathered:

- teachers had to fill pre and post questionnaires on perceptions and attitudes;
- two interviews were conducted with teachers;
- short questionnaires were handed out after each inquiry activity;
- small and large group discussions on models in general and nanoscale phenomena models were audio recorded; and
- teachers' lesson plans were examined.

Varying results were obtained from this first professional development session concerning inquiry teaching, conceptions of models, and how teachers manage to add nanoscale phenomena to their science lessons.

Inquiry-teaching

The research led by Bryan et al. in 2007 highlights that teachers enrolling for this workshop considered that in general they had a good understanding of inquiry learning and teaching. In addition, all participants reported to have taken this course because they wanted to learn about nanoscience. Consequently they were not especially willing to attend courses on pedagogy. However, in spite of some teachers' perceptions, the authors assert that the results tend to show that many of them needed to revisit their knowledge and beliefs about inquiry teaching. It seems to us interesting to examine these findings in the light of the call for using nanoscale science and engineering introduction in classrooms to profoundly reform and transform the way science is taught in secondary classrooms (Schank et al., 2007; Hurd, 2002).

Investigations of teachers' conceptions of models

As conceptions held by teachers may strongly influence students' conceptions and understanding of nanoscale science and technology, some researchers deem it worthwhile to investigate them in order to design relevant professional development. We found for example one research project questioning teachers' conception of spatial scale (Jones, Tretter, Taylor, & Oppewal, 2008). Daly and Bryan (2007) for their part, during this design-based research, starting from the point that teachers will impact on pupils' conceptions of models and of the phenomena the model represents, sought to understand teachers' conceptions of the role and use of models in inquiry-based science teaching. They found that the most commonly held conception consisted of considering models as being mainly useful for 'show-and-tell' purposes. In addition, although the activities used models of nanoscale phenomena for inquiry purposes, it didn't seem, according to the authors, to have influenced the models teachers chose to present.

How to add nanoscale phenomena to science lessons?

Finally, to help teachers build their own answer to this question, teachers had to create their own nanoscale science and engineering lesson. They also had to examine state standards to find which ones were addressed by their teaching proposition.

Vetting the lesson plans of the first workshop session in 2006, cast light on two points. First, teachers seemed more likely to incorporate nanoscale science and technology as extensions rather than adding a completely new lesson on a particular nano-specific topic such as self-assembly (Daly et al., 2007). In addition, to these authors, teachers did not really give an insight into the interdisciplinary nature of nanoscale science in their lessons. Indeed, when it came to identifying in the curriculum where teachers could introduce nanos, they spontaneously referred to their own discipline's standards. To the authors of the articles on NCLT's professional development (Daly et al., 2007), this emphasises the need to develop teachers' awareness of the value of connections between disciplines and to encourage them to spend time teaching a topic they consider beyond their traditional courses. As they remind us, this idea is hard to convey since teachers already often feel short of time to teach an over-crowded curriculum.

Bearing these research results in mind, the research team offered this professional development programme with slight changes and the second session was held in 2007. The same research team studied it. In particular, attention was paid to the factors impacting on teachers' lesson choice and once again on how teachers introduced nanos to their lessons. This time teachers were asked neither to modify nor to create a lesson on size and scale since the research team deemed that 'it did not directly address a nano-phenomenon' (Hutchinson et al., 2009). Teachers implemented the lessons developed during the summer school, and as they gathered on the occasion of a followed-up week-end programme, they expressed why they had selected this lesson and how successful its implementation had been. In addition, one of the 12 participants was interviewed after giving her lesson in front of the class.

According to this research, five main factors appear to have influenced the teachers' choices when introducing nanos in their lessons: relevance, student motivation, inflexibility of the curriculum, technical consideration and content knowledge. In our opinion, these last two points in particular, demand careful consideration. Indeed, as reported in the article, some teachers noted that when students started asking questions, they did not feel they had a sufficiently solid scientific background to answer. The interviewed teacher even said that she would teach nano-related topics more readily if she possessed stronger content knowledge. She also admitted that she did not think she would have been able to do the lesson without the assistance of a professional development staff member in the classroom with her.

4.3. Summary and discussion

Concerning professional development, some authors describe the reasons why teachers may *a priori* be deterred from introducing nanosciences and nanotechnologies in their classrooms (Schank et al., 2007), while in other studies, researchers detail empirical work on teachers' professional development on nanotechnologies programmes (Bryan et al., 2007; Daly & Brian, 2007; Daly et al., 2007; Hutchinson et al., 2009; Tomasik et al., 2009). Among the empirical studies presented here, one describes the design of an on-line environment to allow teachers to follow nanosciences and nanotechnologies courses (Tomasik et al., 2009). The other ones investigate an NCLT programme for teachers' development.

The results of the empirical studies – although one should not rush to conclusions, owing to the small participating cross-sections – stress difficulties in implementing nanosciences and nanotechnologies lessons (Hutchinson et al., 2009) especially in trying to achieve interdisciplinarity (Daly et al., 2007). Apparently, this problem is not specific to nanosciences and nanotechnologies. Yet, it becomes particularly salient, if it is crucial to multiply connections between traditional disciplines to teach cutting-edge nano-related conceptions. In this regard, the research team studying the NCLT's programme suggest using 'nanoscale science and engineering' as a starting point to create interconnected knowledge between it and what is designated by traditional disciplines (Hutchinson et al., 2009). This converges with the 'Big Ideas of Nanoscience and Engineering' document (Stevens et al., 2009a) where the authors wrote that nanoscience may foster more interdisciplinarity in the curriculum. To some extent, this request also echoes one of the preoccupations voiced by Schank et al. (2007), when they called for nanoscience to be a catalyst to reform the US STEM educational system.

In addition, Bryan et al. (2007), who studied the NCLT's programme, also side, in a sense, with this position since they emphasise that introducing nanosciences and nanotechnologies in secondary classrooms cannot spare researchers and teachers from taking a broader reflection on pedagogy and on where these nano-centred lessons can fit into the curriculum.

Furthermore, all the teachers taking part in these two professional developments were volunteers. They represent only a small fraction of teachers not necessarily representative of the rest of their colleagues. In addition, as they applied for these courses, they were certainly eager to learn new things on nanoscale phenomena and we can also assume they were rather inclined to introduce nanosciences and nanotechnologies in their lessons. It is inevitable some teachers may prove more reluctant to integrate these innovative contents. Indeed, introducing these cutting-edge science contents in classrooms demands from them a considerable amount of extra work and, as reported in these studies, even after attending a nanoscience professional development programme, teachers may not be sufficiently at ease or may lack the opportunity to implement nano-lessons. In this connection, the courses mentioned in this review took place partly or entirely during the summer. Some authors have even pointed out that they sometimes found it difficult to strike a balance between asking too much from teachers and demanding from them sufficient commitment so that the programme could remain meaningful (Bryan et al., 2007). Regarding this problem, an on-line collaborative environment presents a significant advantage: it allows much more flexibility and brings together teachers who may be living far from universities.

Eventually, the only justification put forward by Tomasik et al. (2009) to implement this on-line course in order to introduce ‘nanos’ into classrooms and prepare the next generation of nanoworkers, seems to us a debatable argument to plead for introducing nanosciences and nanotechnologies in secondary school. Nevertheless, it remains difficult to assess through the reading of this article, whether this professional development was designed as a mere promotion of nanosciences and nanotechnologies development or if it strongly emphasised questions raised by these emerging sciences and technologies and strove to empower teachers to confront them.

5. Concluding discussion

This review does not intend to be exhaustive. It merely gives an inevitably subjective insight into the new field of science education called nano-education. It was all the more difficult to confront research results as the number of nanosciences and nanotechnologies education studies published in peer-reviewed journals remains relatively low. The examination of these articles leads us to wonder whether the incorporation of nanosciences and nanotechnologies in secondary school curricula poses genuinely new questions. Does it not simply echo more ancient concerns? Interdisciplinarity and training teachers to teach new content have by no means arisen along with the coming of nanosciences. However, in our opinion, one of the distinctive features of nanosciences and nanotechnologies is to bring together all these difficulties.

In addition, as we mentioned before, we only presented in this review studies referring to the US educational system. However, many countries are aligning with the US by currently investing generously in nanotechnologies and nanosciences (for example, in France, the Nano-INNOV initiative was launched in December 2008) and, even though this was not apparent in the corpus of articles we gathered, different actors of many countries are concerned by the educational questions raised by nanos.

5.1 Nanosciences and nanotechnologies?

Throughout this review, we mentioned both nanosciences and nanotechnologies. Nonetheless, we were struck by the fact that the authors of many articles (Daly et al., 2009, Hutchinson et al., 2009, Stevens et al., 2009a) do not use the terms 'nanosciences' and 'nanotechnologies' but only refer to 'nanoscale science and engineering'. We hypothesised that, facing the awkward question of definition, these authors may have been willing to underline, as mentioned in the book 'The Big Ideas of Nanoscale Science and Engineering' (Stevens et al., 2009a), that the concepts they were dealing with were not exclusively linked to the ill-defined notions of nanosciences and nanotechnologies but to more general concepts of science.

5.2 Nanosciences, nanotechnologies and society?

In addition, although the 'Big Ideas' for secondary school nano-education included an item entitled 'science, technology and society', we did not encounter in this review any article studying nanotechnologies as a 'sociotechnoscientific' issue. However, a few attempts to introduce 'nanotechnology and society issues' at middle school level have been made within the context of an NSF-funded programme at the University of Wisconsin-Madison. This programme consisted of training graduate and undergraduate students to 'bring nanotechnology to the public'. As a result, activities have been created for middle school students. Nevertheless, although teaching material is available on the website of this university and an account of these activities can be found (Zenner & Crone, 2008), it seems to us that to what extent these activities could contribute to the acquisition of a 'nano-literacy' has not been yet thoroughly explored. Berne (2008) also asserts the significance of introducing ethics not only at graduate and undergraduate level but also in high school. She examines ethical issues in nanosciences and nanotechnologies and distinguishes three overlapping 'levels of inquiry' in nanoethics. In addition, she indicates suggestions of materials that could be used to kindle students' interest and participation.

In addition, experiences taking into account ethical and societal aspects of nanosciences and nanotechnologies are proposed at university level (Hoover, Brown, Averick, Kane, & Hurt, 2009; Jaszczak & Seely, 2008; Miller & Pfatteicher, 2008; Sweeney, 2006; Tahan et al., 2006; Toumey & Baird, 2008; Zenner & Crone, 2008). Nonetheless, many of these references only give narrative accounts of different innovative courses, listing goals assigned to these initiatives, difficulties encountered, decisions made about contents and persons involved in developing and teaching the courses.

Sweeney (2006), in an article aiming to identify and analyse how researchers working in the fields of nanosciences and nanotechnologies at the University of Central Florida as well as science and engineering undergraduates participating in an NSF-funded programme conceptualise the social and ethical dimensions of their work, also relates how he designed a seminar on social and ethical issues that took place during a summer programme.

Tahan et al. (2006), for their part, from the University of Wisconsin-Madison, outline a discussion-based undergraduate course open to students from different disciplines, from the humanities to engineering as well as from the social or natural sciences. The course entitled 'Nanotechnology and Society', was designed and led for a semester by graduate students who had followed specific 'nanoscale science and engineering and STS courses' during the previous half-year. The goals assigned to this course were the following:

- Introduce the broad field of nanotechnology and the basic science and technology.

- Consider the societal implications of nanotechnology in the context of social, scientific, historical, political, environmental, philosophical, ethical, and cultural ideas from other fields and prior works.
- Develop questioning, thinking, idea producing, and communication skills, both written and verbal. (p. 444)

This course is part of the programme of initiatives implemented at Wisconsin Madison University to teach 'nanotechnology in society'. The structures and purposes of these programmes are also detailed by Zenner and Crone (2008) and Miller and Pfatteicher (2008).

Considering that 'social and ethical implications' had to be integrated in university science courses to ensure that future scientists wouldn't neglect them, Hoover et al. (2009) have also implemented a university course entitled 'Small Wonders: The Science, Technology, and Human Health Impacts of Nanomaterials.' Their three stated goals were to foster interdisciplinarity, to familiarise participating undergraduate, graduate and PhD students with the basic science associated with nanotechnology as well as to expose them to some of the ethical and social implications of nanotechnologies.

Physicist John A. Jaszczack and historian Bruce E. Seely (2008), for their part, relate their efforts and difficulties in incorporating nanosciences and nanotechnologies into the curriculum for first year engineering students of the Michigan Technological University. They sought to give equal importance to basic science, engineering education and societal implications of nanosciences and nanotechnologies.

Finally, Toumey and Baird (2008) (respectively cultural anthropologist and philosopher) relate the different initiatives taken at the University of South Carolina (USC) to 'nurture a nanoliterate university community'. They describe different programmes and activities from undergraduate courses to outreach programmes for 'laypersons', on societal and ethical interactions with nanotech, preferring the term 'interactions' to implications to render the idea of a co-evolution of 'nanotech' and society. Having enumerated a collection of initiatives taking place in their university, these authors nevertheless recognise:

> we need to develop a plan for the metric assessment of nanoliteracy at USC: quantitative measures of nanoliteracy and its progress, and qualitative interpretations of participants' attitudes and values, to complement narrative accounts like this one. (p. 588).

Indeed, as we underlined, many of these works, with a few exceptions – for example, Sweeney's article (2006) – barely relate attempts to introduce social and ethical interactions with nanosciences and nanotechnologies into undergraduate or graduate curricula. Even if they are valuable examples of efforts to introduce students to social and ethical aspects of nanosciences and nanotechnologies, they do not really explore, for the majority of them, to what extent they contribute to the development of a 'nanoliteracy'.

Nanosciences and nanotechnologies have indeed interactions with society. Nanoparticles toxicity for example remains largely unknown. As many countries (because of the economical perspectives opened by nanosciences and nanotechnologies), have engaged in a fierce competition to develop them, ways to ensure the protection of workers handling nanoparticles and of consumers buying products containing them are questioned. Measures to be taken to protect the environment from nanoparticles dispersion are also discussed. Furthermore, nanoelectronics leads to smaller and faster devices with increasing autonomy. As a result, some argue that individual liberties are jeopardised by the development of these invisible devices that could be used for surveillance purposes or even to intrude on people's privacy (Schummer, 2007). Different issues are also raised by the developments of nanomedicine (Gordijn, 2007). In addition, at the nanoscale, physics, biology, chemistry, computer science and cognitive science can share common objects of studies, leading to a 'convergence'. As bio-nanotechnologies may affect the human to 'improve its performance' (Roco & Bainbridge, 2002), ethical concerns are raised by these human-enhancement projects (Dupuy, 2004) in particular if these 'improvements' are implemented for military purposes (Schummer, 2007).

Consequently, nanosciences and nanotechnologies elicit hopes and fears echoed by the media and even science fiction. Assuming that it's part of a school's duty to provide future citizens with tools to understand debates and make responsible decisions in a society pervaded by nanos, it seems to us legitimate not to neglect this 'science, technology and society' aspect more than any other. The avenues to implement such teaching, to integrate them in the curriculum and to assess them in secondary school, remain open and need careful study. To understand nano-related concerns, students must obviously master some scientific content, but fostering critical thinking among students must not remain wishful thinking especially as nanotechnologies' fast development is controversial.

5.3 Teachers' professional development about nanosciences, nanotechnologies and society?

In the same vein, assuming that nanoscale conceptions held by teachers will affect those of their students, how they conceptualise the ethical and social dimensions of the development of nanosciences and nanotechnologies may affect the place and time they devote to these aspects. In addition, one can suppose that the content teachers are taught during professional development programmes will certainly also have consequences for what they consider most important to teach in their classroom. Accordingly, the content of these programmes is far from neutral. It may affect which and how nano contents will be taught. Thus, in our opinion, they must be thoughtfully chosen to remain consistent with the answer assigned to the question: why do we make the choice to introduce nanos into secondary school? Is it only to provide the next generation of nanoscientists, as some authors of an empirical study on teachers' professional development (Tomasik et al., 2009) published by the *Journal of Nano Education* concluded?

6. Conclusion

Throughout this review, we identified four salient aspects in the science education literature on the introduction of nanosciences and nanotechnologies in secondary schools: reflections preceding the design and implementation of a nano-oriented curriculum; studies on nano-related concepts; articles on the utilisation of particular learning activities coupling haptics to an AFM; studies of teachers' professional development. We also underlined the lack of studies on the aspect 'science, technology and society' in secondary school. Although the purpose of achieving 'nanoliteracy' is often assigned to the introduction of nanosciences and nanotechnologies in secondary school, ways to contribute to a comprehensive understanding of nanosciences and nanotechnologies and of their societal and ethical interactions have still to be thoroughly studied. Indeed, many questions are raised by the development of nanosciences and nanotechnologies and for many different reasons, nanosciences and nanotechnologies development is controversial. It calls upon representations and values and raises conflicting interests and debates. Both social and scientific aspects[6] play central roles in these controversies. As a result, following the example of many science educators advocating inclusion in science classrooms of these kinds of dilemmas where science and society factors are inseparable (Sadler, 2004), 'nanos' can be considered as a socioscientific issue. Accordingly, to contribute to the development of the 'nanoscientific literacy' of high school students, it would be interesting, in our opinion, to explore the possibilities of a practical educational approach to nanosciences and nanotechnologies, with a discussion throughout of the diverse arguments of the controversies raised by their development.

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Notes

1. The particular attention paid to a potential influence of ethnicity on results has to be considered in the light of the fact that the articles in this review were mainly US studies.
2. A haptic interface is a tool rendering the sense of touch.
3. In this second research project, authors do not specify whether they successfully inactivated completely the haptic feedback. They merely write about a 'cutoff' and might have improved their device to cancel or almost suppress the haptic feedback.
4. Concerning this latter suggestion, an exploratory and preliminary research investigating the conceptions of this particular population has been implemented by some of these authors (Jones, Taylor, & Broadwell, 2009b). Its goal was to explore how accurate students with visual impairments conceptualizations of the spatial size of objects and distances over many orders of magnitude were, and to compare them to students that were not visually impaired.
5. Consensus about the 'Big Ideas' of nanoscale science and engineering had not been reached at the time the first summer school programme was designed.
6. Speaking here of 'technoscientific aspect' would be more accurate.

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