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Interactive Visualization for Learning and Teaching Nanoscience and Nanotechnology

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Abstract

Nano education involves tackling the inescapable task of conceptualizing imperceptibly small objects and processes. Interactive visualization serves as one potential solution for providing access to the nanoworld through active exploration of nanoscale concepts and principles. This chapter exposes and describes a selection of interactive visualizations in the literature, and reviews research findings related to their educational, perceptual and cognitive influence. In closing, we offer implications of interactive visualization for learning and teaching nano.

I. INTRODUCTION

The impact of the rapid development and application of nanoscience and nanotechnology (hereafter referred to interchangeably as nano) in society increases the need to cultivate a nano-skilled workforce as well as a nano-literate public (e.g. [Laherto, 2010]). At the same time, although developing meaningful and effective instructional strategies to teach nano is a challenging and certainly not trivial assignment for science educators [Xie & Lee, 2012], nano offers an exciting basis to ignite students' interest and motivation in science [Blonder & Sakhnini, 2012]. Furthermore, exploiting the interdisciplinary nature nano serves as a powerful platform from which to communicate otherwise traditionally taught science concepts (e.g. [Schönborn et al., 2014; Delgado et al., 2015]). Rising to the challenge of developing effective nano education channels calls for the implementation of meaningful nano education interventions in both formal (e.g. schools) and informal (e.g. science centers) settings. One potential avenue for contributing to this mandate is in the use of scientifically-informed interactive digital visualization as a conceptual tool for accessing otherwise imperceptible, complex, and counterintuitive nanoscale structures and processes (e.g. [LightFeather, 2006; Xie et al., 2011; Schönborn et al., in press]). In unpacking this notion, this chapter focuses on the role of interactive digital visualization in nano education. The four-fold aim of the chapter is to:

- (1) Argue why and how interactive visualization is a powerful tool for granting conceptual access to the nanoscale.
- (2) Describe a selection of interactive visualization environments available in the literature for learning and teaching nano in formal and informal settings.
- (3) Review international research conducted on the use of interactive visualization in nano education, and,
- (4) Consider implications of the research findings for implementing interactive visualizations in nano education praxis.

II. INTERACTIVE DIGITAL VISUALIZATION AS A TOOL FOR ACCESSING THE NANOWORLD

A. The importance yet challenge of accessing and visualizing the nanoworld

According to Stevens et al. [2010], development of nano literacy within society needs to be based on a solid understanding of the structure and behavior of matter at a fundamental level, including important determinants of emergent properties thereof. Multiple aspects of the nanoworld, which makes it challenging to comprehend, plague this process. For example, the fact that adhesive forces between surfaces dominate over gravity in the nanoworld means that intuitive ideas about object manipulation no longer hold [Marchi et al., 2005]. However, perhaps the most notorious difficulty in understanding the nanoscale is making the mental leap across spatial scales required to interpret the size of objects and relative distances at the nanoscale [Tretter et al., 2006; Millet et al., 2013].

Conceptualizing nanoscale objects and the links between nanostructures and material properties is made particularly difficult by the inaccessibility of the objects to direct visual perception [Shabani et al., 2011]. Work by Swarat et al. [2011] indicates that there is a strong influence of visual experience on students' understanding of size and scale. They found that students tended to think of the world as divided into realms of scale separated by "landmark objects". This effect may have wider implications for small scales compared to large scales, since long distances have multiple familiar visual cues (e.g. mountains, the moon and stars). In contrast, objects at scales smaller than 100 micrometers cannot be associated with any visual cues at the corresponding scale. Consistent with this reasoning, Tretter and coworkers found that students' and experts' size estimation accuracies declined linearly when scales were larger, whereas accuracies dropped abruptly when crossing the threshold of visibility at scales too small to perceive [Tretter et al., 2006].

The lack of discernible "landmark objects" at the nanoscale could be alleviated by creating familiarity with certain nano-objects, and using these as scale units when considering other imperceptibly small objects [Tretter et al., 2006]. For example, ball-and-stick models of molecules are symbolic representations that may in some respects convey the nanometer scale to the general public, and could therefore be built upon in fostering an understanding of nanometer scale events [Batt et al., 2008]. However, utilizing such strategies requires educators to develop curricula, instructional methods, and environments to support learners' engagement with nanoscopic objects and processes [Tretter et al., 2006].

B. The essential role of visualization in making the imperceptible nanoworld visible

Progress in nanoscopic imaging technology has provided a view of how building blocks of nature interact at the atomic level [LightFeather, 2006]. This development allows scientists and engineers to not only image but also manipulate materials and structures at the nanoscale [Wansom et al., 2009]. Many educators agree that physically manipulating and handling nanoscopic entities may be an effective component in learning nanoscience (e.g. [Hong et al., 2010]). However, irrespective of the technology used for imaging and manipulating the nanoworld, there is a step in which the measured data are transformed to make them accessible to our senses. Thus, visualization of nanoscale structures and their organization into macroscopic applications is a crucial proviso in bridging the invisible nanoworld and our sensory experiences [O'Connor & Hayden, 2008]. Hence, visualization techniques, methods and tools play an essential role in unveiling and conceptualizing the structural and dynamic complexities of the imperceptibly small nanoscale [Goodsell, 2011].

In 2005, a workshop on the integration of nanoscience and nanotechnology into science education identified the importance of models and simulations for curriculum development in nano education [Sabelli et al., 2005]. Models and simulations are indeed invaluable in providing scientific sense of structures, properties and behaviors of nanoscale phenomena, as well as for designing structures with desired properties in the nanotechnological engineering of materials and devices [Gilbert & Lin, 2013; Wansom et al., 2009]. For example, work by Daly and Bryan [2010] on teachers' use of models in nanoscale science and engineering education has found that students' interaction with models support the conceptualization of nanoscale objects and phenomena. Here, teachers intended use of models is often associated with their use as tools for visualization. This can include how interactive models such as interactive simulations, where students get to adjust and alter simulation parameters in the interpretation of nanoscale phenomena, can serve as a platform for students to be actively involved in the construction of their own nano-related knowledge.

Given the above, current literature suggests that one potential approach for constructing understanding of the nanoscale is through exploiting immersive and interactive visualization technology as a meaningful opportunity for learning and teaching nanoscience (e.g. [Jones et al., 2013; Dede, 2009]). In addition, developments in web-based technologies for scaffolding access to information, remote laboratory experiences, and interactive visualizations show promise in promoting active learning, and may support students' engagement in learning difficult topics and tasks related to nano (e.g. [Harmer & Columba, 2010]).

C. Technical architectures for interactive visualization of the nanoworld

In the current chapter, we define interactive visualizations as computer-based representations of models or data sets that allow humans to explore scientific concepts. Thus, while the direct instrument output delivered from scientific measurement equipment may be viewed as both a case of visualization and interactivity, we exclude the educational use of authentic laboratory equipment from this chapter unless it contains an explicit component of feeding the data stream into a virtual learning space (e.g. in the case of the *nanoManipulator*, see later).

In approaching the different strands of development for interactive visualization, the employed technologies can be scaffolded by considering the concept of a virtual reality system. Such systems are arguably the most advanced type of visualization while also offer great potential for scientific visualization in nano research contexts [Sharma et al., 2005]. Virtual reality applications can grant users access to imperceptibly small scales and may therefore be a potentially rich pedagogical tool for nano education. Virtual reality refers to computer systems that manifest the following three components. These comprise of: 1) a computer-generated three-dimensional virtual environment, 2) an interface between the virtual and the real environment consisting of equipment that provides stimuli to the user while also monitoring the user's actions, and 3) a software application that controls the equipment in generating an immersive experience for the user. Immersion is a key factor in creating a sense of presence and allowing a natural and intuitive human-computer interaction based on fundamental human cognitive mechanisms [Bowman & McMahan, 2007].

However, implementing virtual reality systems is associated with certain challenges in relation to hardware as well as software. The hardware must provide appropriate sensory stimulation while also being sufficiently sensitive in monitoring the user's actions. Meanwhile, the software needs to be able to provide a context, render outputted stimuli and allow users to intuitively navigate and interact with the system. Here, the sense of vision is typically one main focus in most virtual reality systems given that it can provide a strong sense of presence. Herein, various depth cues can be graphically rendered to provide a sense

of spatial relations and surrounding context. Among these cues, the stereopsis that results from the disparity between the two views that are perceived by the eyes is the most important for visual scenes at close distances. Other important visual cues for depth include shadows, motion parallax and perspective views. Over the years, graphical technologies ranging from cathode ray tube TVs to head-mounted displays have been used to communicate virtual visual information. Today, TVs that provide 3D through stereopsis have become commodity hardware, although their potential for creating affordable virtual reality systems has not yet been fully exploited. Mobile phones represent another technological trajectory for virtual reality purposes, in that the high-resolution screens, motion tracking and high performance processors in such devices allow them to be used as components of simple head-mounted displays (current examples include *Google Cardboard* and *Samsung Gear VR*). In addition, developments within the computer gaming industry have resulted in multiple options for pure head-mounted displays.

The human haptic sense, which combines touch and kinesthetic perception, can also be included in virtual reality systems via haptic feedback devices. Although a range of such devices has been presented in the literature, readily accessible equipment for touch interaction is typically limited to simple vibration to indicate events (e.g. vibrotactile feedback on a smartphone), and robotic equipment that provides mechanical force feedback to simulate aspects such as texture and spring-like forces. In addition, recent research findings indicate that carefully designed visual representations of forces may actually provide an intuitive sense of force interactions at a cognitive level without any actual force feedback [e.g. Palmerius et al., 2014]. The sense of hearing is also frequently included in virtual reality systems. In this regard, sound can render an atmosphere that further deepens the sense of presence as well as provide cues about events and processes that may be outside of the user's field of view [Hendrix & Barfield, 1996]. For instance, recent advanced technology for 3D sound takes acoustics of hearing into account by using head-related transfer functions.

Based on this description of virtual reality systems, the interactive visualizations identified in this chapter are essentially different manifestations of such technology depending on the application at hand. Thus, interactive visualizations can be equipped with different technologies in various configurations in terms of display and interaction techniques, the targeted sensory modes (potentially including additional senses such as olfaction), and the level of immersion. Although technology is an important aspect of interactive visualizations, the choice of actual content is at least as important for successful educational application. Indeed, to be able to leverage the power of such systems it is necessary to construct virtual environments that encapsulate the salient properties and behaviors of relevant concepts. This is true whether the intended message is to convey physical and abstract objects or to simulate the social dynamics of a complex virtual world with artificial beings.

D. Cognitive perspectives on granting access to nano concepts through interactive visualization environments

Formal and informal science education settings are witnessing an increased use of interactive digital tools for communicating scientific knowledge. Interactive visualizations offer users an opportunity to construct knowledge driven by one's own actions, such as the direct manipulation of visual or multimodal content on a screen, or in a virtual environment. Properties of modern interactive visualizations map onto Meltzoff et al's [2009] "new science of learning" by intersecting neuroscience, psychology, and education. The theory integrates three known foundations of human learning, namely, that learning is computational (we use statistical patterns obtained from the environment and our prior experiences to learn), learning is social (social interaction and interactive cues affect and can enhance learning), and learning

is supported by linking perception and action. It follows that by actively linking perception and inputted action, interactive visualizations can provide a cognitive gateway for students and citizens to visualize objects, relationships and processes. Similarly, the tenet that learning is computational and social can be mapped to the potential of multimodal environments to exploit powerful multisensory learning experiences and that sharing cognitive resources in collaborative digital learning spaces may be effective for learning science concepts. Thus, deploying interactive representations of nano knowledge could have a deep-seated influence on understanding nanoscale objects and processes.

The potential learning benefits of interactive visualization find further support in the theory of embodied cognition, which purports that constructing scientific knowledge is intertwined with our sensorimotor interactions in the world (e.g. [Wilson, 2002; Amin et al., 2015]). According to Reiner [1999], the integration of embodied experiences into learning may indicate why tactile feedback affects the learning of scientific concepts. Her study investigated students' construction of force field concepts mediated by a tactile device. Reiner suggests that such a bodily experience allow students to tap non-propositional embodied knowledge, which directly relates to acts involving physical objects without concepts or symbols as mediators [Reiner, 1999]. Multisensory information offered by modern interactive visualizations could thus stimulate learners' integration of their embodied knowledge into the learning of abstract and complex nano-related concepts [e.g. Höst et al., 2013; Schönborn et al., 2011].

In addition, modern virtual and augmented reality technology may harbor further cognitively advantageous properties that could have beneficial impacts on learning with interactive visualizations. In this regard, creating a sense of virtual presence (i.e. the sensation of being 'in' a virtual world) has been associated with increased learning engagement (e.g. [Dede, 2009]). Presence may be strongly induced in immersive systems where the visual display provides users with a surrounding experience in combination with a matching between the displayed information and the users' body movements [Slater & Wilbur, 1997]. As an example of the latter, research indicates that induced sense of presence is stronger when the display provides a perspective that is responsive to the position of the user's head [Hendrix & Barfield, 1996]. Similarly, augmented reality applications provide potential advantages by providing a multisensory experience that engages multiple perceptual pathways for learning while also providing a natural interface for interaction and exploration that is not filtered through the relatively limited mechanisms provided by, for example, a computer mouse [Gillet et al, 2005].

III. EXAMPLES OF INTERACTIVE VISUALIZATION ENVIRONMENTS FOR LEARNING AND TEACHING NANO

Our review of the literature has revealed multiple interactive digital environments to visualize and communicate nano-related concepts for educational purposes that draw on various technologies and forms of implementation. We have synthesized the emergent literature into five categories of interactive visualization systems, presented as follows.

A. Microscope probe-based multisensory platforms

One prominent trajectory in the recent literature is projects where learners interact with advanced systems for scanning probe microscope (SPM)-based nanoscopic exploration of surfaces. Among these, atomic force microscopy (AFM) and scanning tunneling microscopy (STM) are the dominant principles. For example, Blonder et al. [2010] have heralded AFM as a pedagogically powerful interactive tool for visualizing the nanoscale. According to these

authors, AFM can provide meaningful inroads into students' learning about molecules, which in turn can increase excitement toward nanoscience. In addition, students' use of AFM can help traverse reasoning about size and scale from the micro to the macro, a perennially challenging and well-documented demand of science education (e.g. [Jones et al., 2013]).

Interaction through an AFM can be designed so that users can physically manipulate nanometer-scale objects such as viruses, while simultaneously receiving a visual and kinesthetic experience of the nanoworld [Tretter et al., 2006]. This potential has been successfully exploited in the development of the *nanoManipulator* (see Fig. 1), which employs a haptic force-feedback device that translates SPM signals into kinesthetic sensory experiences [Taylor et al., 1993]. This tool has been introduced into educational settings by Jones and colleagues, who have employed a web-based interactive interface to allow school learners to remotely operate an AFM [Jones et al., 2004]. The same research group has also used pre-recorded AFM data to allow the integration of multiple options for exploration of data without requiring access to the actual laboratory equipment [Jones et al., 2006].

FIG. 1. The *nanoManipulator* connects an AFM with a computer that, in turn, translates the measurement signals into stereoscopic 3D visual feedback and force feedback mediated by a haptic device. In this manner, a user can explore the surface of a sample in the AFM through multiple senses. (Image courtesy of the UNC CISMM.org NIH National Research Resource grant #5-P41-EB0020.)

In a project called Interactive Nano-Visualization for Science and Engineering Education (IN-VSEE), Ong et al. [1999] have developed a digital platform where students can conduct real-time SPM over the internet, participate in a series of interactive educational modules designed around visualizing the structure and properties of nano-scale materials, and access images and visualizations representing different nanoscale materials. The resources are intended for the final two years of secondary education and subsequent transition into the first two years of tertiary education. Similar to the work of Ong and co-workers, Hong et al. [2010] have developed a remote internet-based education module that employs an interface consisting of an AFM, computers, and a webcam connected to the internet. The system offers students (even across different countries) the experience of handling AFM-based equipment while allowing them to explore the morphological and mechanical properties of nanomaterials.

B. Visuohaptic virtual and augmented reality desktop environments

While it is presently most common to have visual information as the single (or at least primary) mode of output while interacting with digital visualizations, other sensory modalities may also be engaged. For example, apart from the nanoManipulator applications described above, haptic technology can also be used to present aspects of visualized scientific models to learners through tactile and kinesthetic perception. Multiple bimodal visualization initiatives have focused on various aspects of molecular interactions. For instance, the current chapter authors have presented an immersive system that combines force feedback with stereographic 3D visual output for exploring electrostatic fields around molecules [Höst et al., 2013]. In this system, learners are provided with a bimodal representation of molecular electrostatic fields in the form of force feedback based on the calculated force strength and direction exerted by the field on a probe point charge, in combination with visual field lines that can be deployed at will by the user (see Fig. 2). Other approaches have focused on the interaction between molecules in protein-ligand systems, with pioneering work produced by project *GROPE* [Brooks et al., 1990]. In such systems, users typically navigate a relatively small ligand molecule while simultaneously experiencing the calculated forces resulting from the interaction between the small molecule and the protein molecule while at their respective relative orientations [e.g. Bivall Persson et al., 2007].

FIG. 2. Example of a bimodal visualization system. A) An immersive stereoscopic 3D workbench is combined with a pen-like haptic device that provides the user with force feedback based on the calculated forces between a probe point (represented by the tip of the virtual stylus) and the electrostatic field around a molecule. The user can experience a visuohaptic exploration of the strength and direction of the fields by moving the stylus and rotating the molecule using a “mouse” with three degrees of freedom, as well as deploy visual field lines (shown in blue) that appear in the vicinity of the probe point. B) The system can provide various visual molecular representations, including a combined ball-and-stick representation of the atom configuration and a surface representation that indicates the true size of the molecule’s electronic density. The topography of the molecule may also be explored by moving the virtual stylus along the surface.

Whereas most digital visualizations for learning nano employ mostly virtual representations of the nanoscopic content, an alternative mechanism is to mix virtual representations with real physical objects. Such augmented reality approaches are becoming increasingly common in science education [Cheng & Tsai, 2013]. In relation to nanoscientific content, an augmented reality application has been developed by Gillet and coworkers in the form of biological macromolecules [Gillet et al., 2005]. In this system, a display of handheld 3D-printed tangible models is augmented by superpositioning graphical representations of molecular properties of the biological macromolecules corresponding to the tangible models (see Fig. 3). This allows users to explore the 3D aspects of the molecular properties by simply manipulating the position and orientation of the model.

FIG. 3. Augmented reality visualization of macromolecules. A) Two tangible models representing protein molecules are superpositioned with virtual information about field properties in the vicinity of the molecular surfaces. The precise positioning of the virtual information is determined by markers on the tangible models. B) A tangible model of a polypeptide backbone superpositioned with virtual information about rotatable side-chains and distances. In addition, the tangible model includes magnets that represent hydrogen bond interactions that form during protein folding. (Images courtesy Arthur J. Olson, Ph.D., The Scripps Research Institute.)

C. Gesture-based immersive virtual environments

Work in our own laboratory has concerned the conceptualization and development of an immersive and interactive virtual environment (*NanoSim*) for communicating nano in public and school contexts (e.g. [Schönborn et al., 2014]). In this work, the developed interactive visualization makes use of 3D TV technology and Microsoft Kinect tracking in allowing users to use hand gestures to view and interact with virtual 3D nano-objects (see Fig. 4). The design of the environment is based on the premise that learners' use of bodily movements (e.g. gestures) to interact with virtual nano-objects may provide opportunities for constructing understanding about otherwise largely inaccessible nanoworld structures and processes.

FIG. 4. A gesture-based virtual reality system for exploring interactions at the nanoscale. A) In a nanomedicine scenario, targeted drug-delivery through functionalized nano-tubes is visualized in immersive stereoscopic 3D using a head-coupled perspective to increase the sense of presence. The image shows nanotubes moving along the surface of a cancer cell. B) Users deploy a grab gesture to make contact with and move nanotubes by forming a ring with their thumb and index finger in the virtual workspace.

Other technological approaches to gesture-based interaction include the use of specialized gloves that include sensors and actuators to measure finger and hand movements as well as allowing tactile feedback. Such devices have been suggested by Sharma et al. to be a potentially useful interface for interaction with molecular visualizations [Sharma et al, 2005].

D. Virtual world and game-based learning environments

Much recent interest has been devoted to the educational potential of harnessing learners' enthusiasm for computer gaming in science education through game-based learning initiatives [Cheng et al., 2015]. However, few nano-related games have been described in the published literature surveyed for this review. One example is *Nanoquest 3D*, wherein learners solve construction problems at the nanometer scale [Blonder & Sakhnini, 2005]. Other initiatives exploit learners' familiarity with flexible preexisting interactive virtual worlds (e.g. Second Life) that are adapted for nano educational purposes (e.g. [McWorther & Lindhjem, 2013]). In addition, Chanunan [2011] has presented work on a game for authentic nanoscience learning called *Nano-X Project*, where players are required to take on the task of managing a joint science research and military development project. Apart from the few nano-related games described in the literature to date, there is likely to be a number of available games that have not yet been described in the published literature or that have been developed outside of academic research contexts (e.g. [<http://nanomission.org/>]).

E. Interactive visual simulations

As computer-processing power has increased so has the application of computational modelling approaches for nanoscientific research. These developments have been accompanied by the educational use of computer-based simulations for nano education. Such educational simulation initiatives range from specialized teaching simulations each constructed to convey a single or a few related concepts, to complex simulations suited for university level learners as a way to communicate computational research methods.

The Physics Educational Technology (*PhET*) project offers online access to graphical interactive simulations developed with the aims of increasing student interest, improving learning, and developing active explorative attitudes to learning [Wieman et al., 2008]. The underlying pedagogical idea is that students will learn as they explore the dynamic visual representations of scientific models. In addition, the simulations typically include a linked set of representations, which aids learners' translation between different representations of the same concept. The simulations are designed to be highly interactive with an intuitive interface. The website contains more than 100 simulations across all educational levels, sorted into categories corresponding to traditional school science topics (i.e. physics, chemistry, biology and earth science) and mathematics. Most of the simulations focus on physics [e.g. Wieman et al., 2010] and chemistry [e.g. Moore et al., 2014]. Although no simulations are explicitly defined as being nano-related, the offered diversity of simulations could be exploited to at least cover some areas of nano. In addition, some of the PhET simulations do engage principles and systems that are nanotechnological in nature, including a simulation

allowing for manipulation of a DNA strand using “optical tweezers” and molecular motors (see Fig. 5 A).

Charles Xie (e.g. [2011, 2011]) has developed an interactive digital environment called the *Molecular Workbench* (MW), which contains several aspects of nano concepts and accompanying available dynamic modeling tools for nano education purposes (e.g. see Fig. 5 B). The MW offers students the opportunity to conduct interactive computational investigations with dynamic visualizations that simulate underlying molecular and quantum dynamics obtained from molecular modelling research [Xie et al., 2011]. In this manner, the authors propose one pedagogical implication of MW is in the opportunity to conduct authentic science in the classroom. Furthermore, the authors see MW as providing many examples of how students can gain an understanding of submicroscopic structures and processes through interactive educational technology (also see [Levy, 2013]). Aspects of the embedded computational content in MW include curriculum-based interactive online classroom experiments that include, *inter alia*, states of matter, chemical bonding, diffusion, and self-assembly, all representatives of topics that link to nanoscience and nanotechnology concepts. Moreover, the authors view interaction with MW as a means to demonstrate the “unity of science” in showing, for example, how emergent biological properties arising from chemical interactions are able to unify conceptual connections between the microscopic and macroscopic fundamentals of the states of matter [Xie et al., 2011].

FIG. 5. Examples of interactive 2D simulations. A) An immobilized molecular motor “pulls” a nano-sized bead via a DNA chain, while the bead is simultaneously influenced by an “optical tweezer” setup. The influence of various parameters on the outcome of the “tug-of-war” can be explored by users. The interface also allows multiple linked displays, in this case showing the potential energy of the bead as a function of position. (PhET Interactive Simulations, University of Colorado Boulder, <http://phet.colorado.edu>) B) Molecular entities with a polar charge distribution spontaneously form structures through self-assembly following random encounters resulting from the molecular motion caused by collisions with solvent molecules (solvent not shown in the simulation). Users can influence the process by moving subunits and manipulating charge strength and type. The simulation is part of an activity that contains a sequence of simulations intended to convey the principles of self-assembly. (Molecular Workbench, Concord Consortium.)

The Network for Computational Nanotechnology has constructed an online platform for open-access nano-related simulations called nanoHUB.org [Klimeck et al., 2008]. On this site, a large number of scientific simulations and other materials are available for users to run online. The overall focus of the project on simulations intended for scientific research means

that only a subset of the simulations are intended for direct educational purposes alone. Nevertheless, nanoHUB.org provides useful resources explicitly for nano education initiatives, wherein simulations and other content are packaged together as curricular units for various topics [Winkelmann et al., 2014].

IV. RESEARCH ON THE INFLUENCE OF INTERACTIVE VISUALIZATION IN NANO EDUCATION

Following the above description of published interactive digital environments for teaching and learning nano, this chapter now embarks on reviewing published research on the influence of these visualization environments in nano education contexts. We used four criteria to select studies for review. Firstly, the study should be drawn from the peer-reviewed international literature (e.g. journal articles or peer-reviewed conference proceedings). Secondly, the work should be concerned (at least in part) with nanoscience, nanotechnology, or related nanoscale concepts by explicitly mentioning the “nano-” prefix in the manuscript text, and not only implying it. Thirdly, the work should include an aspect(s) associated with perceptual, cognitive, educational and/or pedagogical dimensions of the respective interactive visualization in focus. Fourthly, the study should include reporting of human participants’ (such as citizens and/or students) use of a respective interactive environment.

Our search and synthesis of the literature revealed 20 research works for analysis and review. The studies are summarized in Table I and are arranged as per the interactive visualization system types described in section III. Although the set of reviewed publications represent our own opinion of the principle contributions in this area, it may not necessarily be an exhaustive account of all published work available on the topic.

TABLE I. Summary of reviewed studies that have investigated the role of interactive visualization systems in learning, teaching and/or communicating nano-related concepts

Author(s) and year study published	Nano-related concepts and knowledge associated with study	Interactive visualization system	Architecture of the interactive visualization under study	Description of interaction performed to map to and access intended nano-related concepts
Jones et al. (2003, 2004, 2006)	Nanometer scale; microscale; virus morphology and dimensionality (2003, 2004); virus characteristics such as shape, composition, and size; properties and behavior of nanoscale objects (2006)	Probe microscopy in combination with a visuohaptic virtual platform	The <i>nanoManipulator</i> comprises an AFM, a desktop computer, haptic device (e.g. PHANToM), and accompanying software	A student moves a pen-like stylus (that receives signals from an AFM probe) over the surface of a virus sample, and receives a simultaneous 3D visual (200000x mag.) and tactile perception (e.g. hardness, shape and stickiness) of the nanoscale surface (see Fig. 1)
Marchi et al. (2005)	Lennard-Jones (LJ) potential; approach-retract interaction; nanomanipulation; differences between nanoscale and macroscale physics	Probe microscopy in combination with a multisensory virtual platform	A custom-made nanomanipulator based on a multisensorial (haptic, visual and auditory) platform	Various modes of multisensory rendering allow the student to inspect the local surface approach-retract interactions with an AFM probe. The user is able to see, hear and feel the interaction between the sample surface and AFM tip
Millet et al. (2013)	Behaviour of an AFM probe; approach-retract phenomenon; nanomanipulation; perception of the nanoscale; nanoscale mechanics	Virtual microscopy probe with haptic virtual reality system	Virtual AFM probe that consists of a real-time simulation in combination with a 3D graphics interface and a VIRTUOSE haptic device	The AFM simulation provides visual and force feedback of the approach-retract phenomenon. The subject views a graphic analogy of the phenomenon while simultaneously manipulating the haptic device to receive force feedback related to the bending of a simulated cantilever
Vogl et al. (2006)	Nanophysical properties; nanomanipulation; nanoforces; surface topography	Microscope Probe-based visual and haptic augmented reality interface	An AFM-based augmented reality interface that consists of computer graphics and a haptic interface that blends sensed and simulated	A real-time simulation of nanoscale surface interactions is displayed by augmenting graphics derived from noncontact and contact interaction models with force feedback. The user

			information in real time	perceives the simulated information blended with the information sensed by the AFM probe
Höst et al. (2013)	Forces and interactions between nano-objects; shape and topography of nano-objects; relative volume and scale of nano-objects	Visuohaptic virtual reality desktop environment	The semi-immersive virtual environment comprises of mirrored displayed 3D stereoscopic graphics that are colocated with a PHANToM haptic device and 3D mouse	A stylus is used to feel the electrostatic potential around a molecule. The stylus tip is haptically rendered as a positive point charge. Simultaneously, 3D visual properties such as van der Waals radii and electrostatic field lines represent the relative size and scale of these nanoproperties in relation to the molecule (see Fig. 2)
Magnanelli et al. (2014)	Intermolecular forces at the nanoscale; intermolecular interaction	Visuohaptic virtual reality desktop environment	The <i>HaptiChem</i> framework combines the use of a visual interface and Phantom Omni haptic device	A visual representation of a molecule is delivered in different modes of chemical representation (e.g. van der Waals spacefill) and the haptic probe is used to explore the electrostatic field of the molecule and also experience different intermolecular interactions such as hydrogen bonding and halogen bonding
Park et al. (2010)	Electric fields generated by nano-objects; point charges	Visuohaptic desktop simulation	The <i>point-charge simulator</i> combines visual information on a computer screen and force feedback via OMEGA-3 and Falcon haptic devices	Electric fields produced by point charges are visualized while a user simultaneously holds a haptic device to visuohaptically perceive point-charge interactions. A test charge approaching a positive charge is rendered as a repulsive force, while an attractive force is rendered upon a test charge approaching a negative charge.
Gillet et al. (2005)	Bio-nanotechnology; spatial structure; biomolecular	Augmented virtual reality system	The tangible interaction environment allows	A user holds and manipulates a physical 3D model of a complex

	properties; interactions between complex molecules		computer-based volumetric visualizations to be overlaid onto hand-held 3D-printed models	molecule (e.g. protein) and views a computer screen that allows the simultaneous manipulation of the physical model and viewing of an augmented scene of molecular properties such as electrostatic field (see Fig. 3)
Schönborn et al. (2014)	Brownian motion; nano-object collisions and forces; relative size; relative forces; length-to-diameter ratio; binding specificity; “scaling-up” from nano-to-micro-to-macro; nano-toxicity; nano-therapy	Gesture-based immersive virtual environment	<i>NanoSim</i> combines motion tracking of head movement and defined hand gestures (via a <i>Kinect</i>), visual output on a 3D TV and customized simulation software	Citizens and students use a head-coupled perspective and defined hand gestures to reach into the virtual volume and interact with 3D nano-objects. Moving, pulling or pushing the objects serves as the basis for accessing underlying nano concepts in interpreting potential risks and benefits of nano (see Fig. 4)
McWhorter & Lindhjem (2013)	Nanotechnology safety; nanoparticles; nanotubes; nano-related products; safety hazards; safety equipment	Virtual world as a learning environment	A virtual learning environment (VLE) designed within the 3D virtual world of Second Life (SL)	Via an avatar, users embark on a nanotechnology safety tour within SL that renders a nanotechnology safety laboratory. Each avatar can interact within the VLE through learning stations depicting various nano concepts, with the opportunity to apply nano safety equipment to their avatar
Chanunan (2011); Chanunan et al. (2009);	Properties of nanomaterials; size and scale; tools used in nanoscience and nanotechnology; historical perspectives of nano	Game-based learning environment	The <i>Nano-X Project</i> is a computer game-based epistemic platform that combines various scenario, graphic, narrative, and interactive components	The main game scenario involves players tasked by the government to lead the development of new military protection attire for soldiers, by applying the unique properties of nanomaterials. By solving the problem through interaction with computerized agents, players develop nano-related

				conceptual and procedural knowledge
Blonder & Sakhnini (2012)	Size and scale; nanometric scale; surface-area-to-volume ratio (SA/V); shapes of nano-objects; properties of matter at the nanoscale	Game-based learning environment; Interactive visual simulations	<i>Nanoquest 3D</i> is a character-based computer game; <i>The nano effect</i> simulation incorporates different navigation options within various interactive information screens	<i>Nanoquest</i> requires students to construct a nanocar by collecting nano-objects, allowing for conceptualizing different nanomaterial shapes. <i>The nano effect</i> simulation allows investigation of nanoscale properties of matter through concepts such as when object volume decreases, surface atom number increases
Xie & Lee (2012)	Nanomachines; nanosystems; nanoelectronics; nanoscale processes; all-atom, coarse-grained, Gay-Berne, soft-body, and quantum molecular dynamics.	Interactive visual simulations	The <i>Molecular Workbench</i> (MW) is a computer software environment based on various molecular dynamics models that provide interactive simulations for virtual experimentation	The learner engages the graphical user interfaces incorporated in the MW environment to explore, model and interrogate simulated nanoscale processes outputted on the computer screen display in real time. Examples of interactive simulations include self-assembly and hypothetical nanosystems (see Fig. 5 B)
Pallant and Tinker (2004)	Nanoscale interactions; atomic interactions; molecular dynamics; phases of matter	Interactive visual simulations	<i>Molecular Workbench</i> (MW) in combination with <i>Pedagogica</i> , a software script that structures the user's interactive experience as a linked hypermodel	The user interacts with an MW molecular dynamics model through various options such as placing atoms into a container and manipulating variables such as mass, charge and location. While doing so, the <i>Pedagogica</i> application monitors the user's interaction and responses and structures the learning trajectory
Shipley et al. (2008)	Nanoscale self-assembly; dipole bonding; dipole attraction and repulsion; charge position; molecular	Interactive visual simulations	<i>Molecular Workbench</i> (MW)	The learner engages with the MW self-assembly simulation through various interactions. Starting from a representation of random molecular

	movement; system energy; molecular shape; reversibility			motion, the student manipulates the dipole charge strength, charge type, charge placement, and molecular shape of nano-objects in subsequent yielding of self-assembled aggregates
Magana et al. (2012)	Various nanotechnology-related concepts including, <i>inter alia</i> , concentration-dependent diffusion; quantum dots; nanowires; nano-materials; carbon nanotubes	Interactive visual simulations	The <i>NanoHUB.org</i> simulations contain educational computational simulation tools based on mathematical models processed on distributed-computing platforms	Interactive nanoHUB simulations are accessed through a web portal, where a participant engages with a user interface to run a simulation related to nanotechnology concepts. Examples of simulations that could be explored included concepts surrounding concentration-dependent diffusion, carbon nanotubes, and quantum dots
Delgado et al. (2015)	Size and scale; relative size; submacroscopic scale and objects; micro-, nano-, and sub-nano worlds	Interactive visual simulations	A computer visualization that displays objects by automatically iterating one object across another to convey the relative size of different objects	Students interact with the visualization to perceive objects (from a hair to an atom) displayed at different levels of scale. For example, an image of a skin cell is overlaid with an image of multiple bacteria to convey the concept that the diameter of an animal cell is equivalent to 15 bacteria placed side by side

We now further unpack the studies presented in Table I in relation to findings on the influence of interactive visualization environments on learning and perception of nano-related concepts. Upon consulting the synthesis below, the reader is requested to refer to the summary in Table I where appropriate, with respect to each respective author(s) or environment of interest.

A. Studies on microscope probe-based multisensory platforms

Jones et al. [2003] have investigated high school students' interactive exploration of AFM data through the *nanoManipulator* interactive interface that allowed for multimodal visual and haptic perception of nanoscale phenomena. The study found that interaction had a marked influence on learners' understanding of nano-related morphological and topographical features of viruses, as well as of relative scale. In addition, the students viewed the interaction as inducing an engaging learning experience. A subsequent study by the authors in 2004 [Jones et al.] demonstrated significant changes in high school students' conceptions of scale with an accompanying transition from a 2D to 3D perception of virus morphology. Results also showed that receiving tactile feedback correlated with an increased engaging and motivating experience. Moreover, a study in 2006 [Jones et al.] confirmed earlier findings that haptic feedback induced a more immersive and engaging environment for middle and high school students, and also influenced students' understanding about the abstract properties and behaviors of nanoscale objects.

In other related work, Marchi et al. (2005) conducted a study on the use of a custom-made nanomanipulator and classical AFM interface on Masters level university students' understanding of nano-object manipulation in relation to the approach-retract interaction. One aspect of the study considered the influence of each of three offered sensory modes (visual, haptic and sound) on students' understanding. Results indicated that different modes played different roles in perception of the phenomenon, with visual cues crucial for determining force threshold, and haptic feedback for determining the nature of the force involved. In keeping on this track, a study by Millet et al. (2013) explored the influence of a virtual AFM probe that combines graphic analogies and haptic feedback on forty-five engineering students' understanding of the approach-retract phenomenon. Findings showed that the researchers' adoption of a graphic magnet-spring analogy and accompanying force feedback improved students' understanding related to cantilever dynamics, and that the bimodal experience was positively received and appreciated by the participants. The authors also purport that the availability of a virtual tactile experience in solving a task could induce more motivation and engagement, while experiencing force feedback could also constrain and focus students' orientation on relevant procedures of the task.

In a final microscopy-related contribution, Vogl et al. [2006] explored subjects' accuracy, usability, and reliability of their developed AFM-based augmented reality interface with tasks involving positioning an AFM probe tip just above, just in contact with, or just below the surface of three different materials. Data analysis revealed difficulties (e.g. positioning the tip just on the surface was most demanding) and benefits (e.g. the system performed well in simulated mode) of using the interface in exploring noncontact and contact nanoforces in relation to nanomanipulation applications.

B. Studies on visuohaptic virtual and augmented reality desktop environments

Results from the current chapter authors' case-based analyses of four students' multisensory visuohaptic interaction with electric fields around molecules [Höst et al., 2013] revealed distinct interrelationships between students' interactive strategies implemented when

executing tasks in the virtual system and the nature of conceptual knowledge deployed. For example, interaction within the virtual environment appeared to provide a bimodal sensory basis for students to dissolve the erroneous view that nonpolar molecules are void of an electric field. In this regard, the case-based data suggested that the force feedback experience may have induced an active integration of electric field concepts with ideas of molecular charge distribution. In addition, the study suggested that multisensory experiences offered by such interactive visualizations could provide a basis for helping learners conceptualize the shape and topography of nanoscale entities, and the relative size and scale of nano-object properties. In other work, Magnanelli et al. [2014] used molecular exploration tasks, interviews, and written surveys to evaluate 19 bachelor level students' use of the *HaptiChem* interface as part of a chemistry course. Aspects of preliminary data analysis indicated that students solved the molecular tasks (e.g. identifying the critical parts of a molecule involved in particular intermolecular bonding) in a more precise manner with haptics activated than without. The data also revealed an increase in students' interest in their learning upon using the interface, and 89% of the students considered the interface to have potential as a device for improving chemistry learning.

The *point-charge simulator* developed by Park et al. [2010] was evaluated by investigating 38 undergraduate students' (assigned either to a visuohaptic or visual only group) learning of electrostatic-related concepts, as well as their attitudes and motivation. The intervention in a pre-/posttest study design consisted of interaction with the simulator in the form of participants examining the electric field and equipotential properties of different charge configurations. Results on a physics concepts test revealed a significant increase between post- and pretest scores in both groups, which indicated that learning benefits were associated with both conditions of interaction. Albeit so, qualitative observations in the visuohaptic group found students to be very positive about their interaction experience in relation to the tasks.

Finally, when it comes to physically augmented modelling systems, Gillet et al. [2005] have evaluated their augmented reality interface in a high school classroom setting, with university biochemistry students, and with practicing molecular biologists. In the first setting, augmented hemoglobin models were used as part of a lesson on protein structure, and pilot results revealed the models as engaging and instructive. The second setting considered augmented amino acid models as part of a lesson on protein structure and function, where pilot observations were conducted while students investigated the role of different amino acids within a protein structure. The third setting investigated authors' colleagues use of the models as bio-nanotechnology research tools in contexts such as biomolecular complex assembly. Results from a pilot evaluation indicated that the models provided an enhanced representation and conceptualization of structural properties.

C. Studies on gesture-based immersive virtual environments

Research conducted by the authors of the current chapter has explored citizens' and learners' interaction with the *NanoSim* gesture-based virtual environment in a science center context [Schönborn et al., 2014]. In one study from the research program, quantitative results obtained from unobtrusive logged interactions from 1600 public visitor activations of the system verified that the environment offers an engaging, immersive, and highly interactive experience. In another study, a think-aloud qualitative investigation with three Swedish students having just completed high school chemistry, suggested that interactive gestural interaction with the system could serve as a cognitive gateway for building nano-related understanding necessary to judge perceived hopes and fears of nano. In addition, analysis also revealed that the interactive nanocontext provided a stimulating yet alternative opportunity for

students to learn otherwise traditional chemistry concepts. Intriguingly, ongoing qualitative data analysis of use of the system at time of writing indicates that citizens create nano ideas that are often divorced of accompanying scientific ‘jargon’, as well as contain the reporting of a pseudohaptic perception of forces between nano-objects, a result that has beneficial implications for the implementation of such technology in classroom use. Herein, it may be well worth exploiting pseudohaptic feedback (e.g. Lecuyer [2009]) in the design of environments where the intention is on accessing understanding of nano-object interactions.

D. Studies on virtual world and game-based learning environments

When it comes to other variants of virtual learning environments apart from those discussed above, McWhorter and Lindhjem [2013] have investigated the influence of their designed nanotechnology safety laboratory in the Second Life (SL) virtual world. The study involved 133 university students from four universities who took a 45-minute tour of the laboratory in groups, where activities for their respective avatars included exposure to learning stations about various nanoparticles and possible safety hazards that face nanoworkers. One main finding from a post-survey presented after the nanotechnology virtual world intervention revealed that 92% of the participants answered in the affirmative to whether they thought that SL could be useful in nanotechnology safety education. In addition, open-ended responses also revealed that the environment allowed trainee nanoworkers to learn from laboratory safety mistakes made in the virtual world, and take such safety implications on board before entering real nanotechnology laboratories.

In other virtual world approaches, work by Chanunan and colleagues [2011, 2009] has dealt with the development of the *Nano-X Project* computer game-based environment for learning fundamental nano concepts. Initial data collected from six high school students in response to a pre-/post conceptual understanding test, focused group discussion and individual interviews showed that participants’ interaction with the game was associated with increased conceptual understanding surrounding size and scale, the meaning of “nanoscience” and “nanotechnology”, as well as historical aspects of nano. The initial findings also revealed that students found learning with the game interface to be a motivating and engaging experience. Apart from the positive results, usability data obtained from the students revealed what future modifications to the game-based environment, such as superfluous text and unrelated graphical components within the environment, could be modified or removed to increase the learning potential. Continuing within the realm of game-based learning, amongst other instructional methods, Blonder and Sakhnini [2012] investigated the influence of interactive visualizations on 60 students’ understanding of basic nanoconcepts when used as part of a ninth grade nanotechnology module. Through interviews and student project-based work, the authors found that although challenging for some of the students, there were positive conceptual outcomes associated with playing the *Nanoquest 3D* game, with one student suggesting, “Only after playing this game did I really understand what is the nano-dimension...” (p. 513).

E. Studies on interactive visual simulations

In continuation of the study by Blonder and Sakhnini [2012] described above, when it came to interaction with *the nano effect* visual simulation to expose students to the idea of SA/V properties in relation to nanometric scale, some of the students found conceptualization of this concept through the interface to be rather abstract and challenging to interpret. Albeit so, in the context of interactive visual simulations, influential work by Xie in the area of representing nanoscale processes has resulted in development of the *Molecular Workbench*

(MW). In Xie and Lee [2012], the authors present results from a pilot study concerned with 22 university students' use of three homework MW modules as part of a solid state physics course. The influence of the modules on students' learning was investigated with a pre-/post-test multiple-choice and open-ended instrument. Results showed a significant increase in students' scores on the multiple-choice items, which suggests that students' interaction with the MW simulations was associated with the observed learning gain [Xie & Lee, 2012]. In an earlier study, Pallant and Tinker [2004] investigated a MW molecular dynamics model concerned with atomic interactions and phases of matter incorporated in the *Pedagogica* platform in a learning activity provided to students across 10 middle and high school classrooms. One focus of the study concerned exploring the influence of the MW dynamic model on students' reasoning about atomic and molecular interaction at the nanoscale. Data obtained from implementation of the activities through pre-/post-test comparisons, analyzing students' reasoning, and conducting student interviews indicated that interaction with the interface led to significant learning gains related to understanding states of matter. The authors attribute the sense of control and interactivity offered by the interface, making explicit connections between macroscopic and microscopic scales, and the offered guided exploration as factors associated with students gained understanding of nanoscale interactions.

While making use of the MW self-assembly simulation as part of a nanotechnology design intervention, Shipley et al. (2008) explored 41 6th grade students' learning of nanoscale concepts related to self-assembly. A paper-and-pencil drawing instrument was included as a measure of students' generation of solutions and predictions around how molecular entities might form different self-assembled aggregates. Results revealed that 77% of the participants gave correct answers to the self-assembly design tasks, and that interaction with the MW simulation significantly influenced students' accurate prediction of self-assembled configurations. Overall, the aforementioned studies conducted on the educational use of MW indicate that interactive modelling is associated with students' attaining an understanding of nanoscale ideas that could be transferred to new learning contexts, a finding that bodes well for suggesting how interactive simulations can enhance nano-related understanding at large [Xie et al., 2011; Xie & Lee, 2012; Pallant & Tinker, 2004].

As part of other research on the role of interactive visual simulations in nano education, Magana, Brophy and Bodner [2012] explored 314 science and engineering university students' perceptions and experiences of the *NanoHUB.org* simulations for learning, as well as measured any differences between graduate and undergraduate students' perceptions of the simulations. Data was collected using an online survey questionnaire following the integration of nanoHub simulations across 20 course and 9 university contexts. Findings revealed that students placed high positive value on having the interactive simulations integrated as part of their learning, although the study identified differences between graduate and undergraduate students' perceptions of simulation ease of use.

Lastly, a recent study by Delgado, Stevens, Shin, and Krajcik [2015] centered on the development of an instructional intervention around the idea of size and scale embedded in a nanotechnology context. Interactive computer simulations were included as part of the pre-/post-test intervention with a total of 66 middle school students from different school districts, where the overarching theme was on how nanotechnology could prevent sickness. Qualitative and quantitative results obtained from interviews prior to and following the intervention revealed a significant increase in students' scale understanding of object sizes including the atom, and viruses and cells, which indicates that students' interaction with the visualization may have had a positive influence on conceptualized size and scale knowledge.

V. IMPLICATIONS OF RESEARCH FINDINGS ON THE USE OF INTERACTIVE VISUALIZATION IN NANO EDUCATION

A. Overall assertions on the influence of interactive visualization for learning and teaching nano

Based on the conducted literature review, extrapolation of findings into overall assertions on the influence of interactive visualization for learning and teaching nano are as follows:

- Sensoriperceptual embodied features afforded by modern interactive visualization environments might be cognitively well-suited to learning abstract and complex nano concepts (e.g. [Dede, 2009; Schönborn et al., 2014; Jones et al., 2006, 2004, 2003])
- Multisensory engagement offered by activating visual, tactile and proprioceptive pathways could provide a natural and intuitive basis for constructing abstract concepts different from indirect interactions (e.g. a computer mouse) (e.g. [Gillet et al., 2005])
- Millennial student users are comfortable and positive about using interactive visualization environments as adjuncts to their science learning (e.g. [McWhorter & Lindhjem, 2013])
- Different sensory modes (and their relative combinations), and different styles of interaction within an environment can play significantly different roles in learners' perception of nanoscale ideas, and offer novel authentic hands-on learning experiences (e.g. [Marchi et al., 2005; Höst et al., 2013; Park et al., 2010; Jones et al., 2006])
- Multisensory interactive environments may be fruitful particularly for learners with low or no nano-related knowledge and could compensate for students with low spatial ability (e.g. [Xie & Lee, 2012; Millet et al., 2013; Schönborn et al., 2014, 2011]).
- Simulation-based modelling through interactive visualization can help students build an integrated understanding of demanding nano-concepts in a self-paced manner (e.g. [Xie & Lee, 2012; Pallant and Tinker, 2004])
- Exposing students to nano ideas through interactive visualization may serve as an alternative and interdisciplinary platform for learning otherwise traditional scientific concepts in physics, chemistry and biology (e.g. [Schönborn et al., 2014])
- Interaction with immersive multisensory visualizations is associated with increased student interest, engagement and motivation in the science content under study (e.g. [Jones et al., 2004; Dede, 2009; Park et al., 2010; Magnanelli et al., 2014; Ong et al., 2000]).
- Students' learning with interactive visualization is linked with the an increased ability to transfer newly acquired knowledge of nanoscale processes to different contexts (e.g. [Pallant and Tinker, 2004; Magana et al., 2012])
- Immersive visualization environments could enhance collaboration and social interaction between students by adding novel actions and opportunities for inquiry-based learning experiences (e.g. [Chanunan et al., 2009; Gillet et al., 2005])

B. Potential challenges of integrating interactive visualization in nano education praxis

Although the literature indicates that interactive digital visualization offers a promising cognitive and pedagogical means for accessing the nanoworld, it is important to consider the potential challenges that accompany implementation in formal and informal nano education contexts. The following three challenges that nano education role players should take heed of are raised for consideration during integration of interactive visualization in practice.

Firstly, it is crucial that practitioners consider the danger of trivializing the complexity and sophistication of nano content through superficial or over-simplified interactive visualization [Laherto, 2010]. For example, Jones et al. [2015] have cautioned that although instructional

visualization is pivotal for communicating nanoscale objects and properties, care must be taken to ensure that the content is interpreted appropriately. Therefore, it is necessary that students and citizens hold appropriate knowledge frameworks to interpret information depicted through newly developed visualizations of nano phenomena. In this regard, given the future impact that nano is bound to have, it is imperative that citizens possess a critical understanding of how visual images are used to communicate nano [Landau et al., 2009], and demonstrate “the ability to discern models that are a translation of scientific data as compared to fictional models” [Batt et al. [2008], p. 1147]. Similarly, Goodsell [2006] has suggested that given the relative infancy of scientific endeavor concerned with visualizing nanoscale entities, it remains a challenge to avoid separating compelling visual stimuli from scientific reality. Thus, student and public interpreters of nanoscience require careful descriptions of what is being visualized, and how, in order to avoid blurring nano-related visual fantasy with science fact.

Secondly, it is essential that practitioners strike a meaningful balance between technological, conceptual, and economical constraints in the implementation of interactive visualization in nano education. Part of this process involves moving beyond the “wow-factor” [Chandler, 2009] and not viewing interactive simulations as a “magic bullet” [Finkelstein et al., 2005], by naively affirming that the mere availability of modern interactive visualization automatically translates into conceptual learning. At the same time, students should be encouraged not to view interactive models used to represent nanoscale objects and processes as mere visualization tools for representation purposes alone. Instead, students should be stimulated to take advantage of the modelling and interactive opportunities afforded by such visualizations as a means of providing conceptual access to the nanoworld [Daly & Bryan, 2010].

Thirdly, integration of interactive visualizations in nano education can be exploited to both excite students about the swiftly growing area of nano as well as improve knowledge acquisition in the classroom [Ong et al., 2000]. Hence, a further challenge to be met is for designers and developers of pre-university science curricula to take the influential cognitive and affective role of dynamic interactive visualization into account when aiming to integrate nano-related concepts and principles effectively [Pallant and Tinker, 2004; Shipley & Moher, 2008]. On this score, interactive simulation and modelling of multiple cross-disciplinary and convergent concepts such as self-assembly, size and scale, and proportion, present concrete and non-traditional opportunities to include nano concepts and principles in school science curricula (e.g. [Delgado et al., 2015; Blonder & Sakhnini, 2012]). In doing so, designing interactive visualizations in this manner could bootstrap the effective integration of inquiry-based curricular materials for technology-enhanced nano education [Magana et al., 2012].

C. Future research on interactive visualization in nano education

This review has presented various interactive visualization systems available to the nano education community and has described research related to their influence on perceiving and understanding nano. In closing, we posit possible avenues for future research inquiry on the role of interactive nano visualization environments for learning and teaching.

Since digital interactive visualizations present authentic yet novel “hands-on” experiences for students to be exposed to nanoscience, and given their general cost effectiveness and flexibility, it could be pedagogically valuable for future work to further explore to what extent “real” laboratory settings could be substituted with interactive visualization tools for modelling and simulating nanoworld concepts (e.g. [McWhorter & Lindhem, 2013]). If feasible, such an approach could increase the accessibility of nanoscience to citizens and students at large. However, meeting such objectives would also require realistic models of

nano-object interactions for reliable and valid nanomanipulation with computational data to be ensured. Hence, as suggested by Sharma et al. [2005] more research on real-time virtual rendering of nanodynamic force simulations (e.g. van der Waals, contact deformation, and electrostatic forces) are required to be developed to capture the complexity of nanoscale interactions.

Although this review demonstrates that nano education-related research on interactive visualization is certainly increasing (all 20 contributions summarized in this chapter are from the 2000s), when it comes to investigating the role of immersive environments for science education overall, Dede [2009] suggests that more future work is required on exploring the specific affordances that such environments provide the learning process. Here, in application of Dede's [2009] stance, one suggested focus is studying the relationship between the nanoscience subject matter at hand and the need for immersion (i.e. when is immersion important, necessary or even favorable for learning different nanoconcepts?). Another is on deducing the most effective combination of situated learning opportunities and immersion environment design for promoting the transfer of learning nano to other contexts (i.e. application of knowledge attained in one situation to another situation, such as from a classroom to a real-world context). On this score, the design of interactive nano environments that harness multisensory features must depend on detailed insight into why and how learning may (or may not) be occurring [Höst et al., 2013]. In this way, future designers of virtual nanoscale environments should pay attention to considering how dynamic interactive visualizations best be constructed to "augment mental processes and not to act as a substitute for those processes" [Levy, 2013, p. 715]. Overall, it is important that any interactive visualizations that foresee contributing to future pedagogical application are informed by research and valid design-based principles (e.g. Finkelstein et al. [2005]) in order to move the nano education agenda forward (e.g. Bryan et al. [2015]).

In conclusion, though there are certainly compelling reasons for the nano education community to be excited about the cognitive potential of interactive visualizations for learning and teaching, in general, much of the research to date has been performed on limited numbers of participants that are often drawn from highly context-specific domains. Continuation of an empirical research agenda for informing the effective design and implementation of interactive visualization in nano education should be expanded to include: more investigations across learner demographics and level, include other formal and informal educational settings, and deploy higher numbers of participants (e.g. [Xie and Lee, 2012]). In doing so, more knowledge will be gained about the educational role of interactive visualization in the nano revolution.

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