Development of an Interactive Immersion Environment for Engendering Understanding about Nanotechnology: Concept, Construction, and Implementation

Konrad Schönborn, Gunnar Höst, Karljohan Lundin Palmerius and Jennifer Flint

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Development of an Interactive Immersion Environment for Engendering Understanding about Nanotechnology: Concept, Construction, and Implementation

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ABSTRACT

The advent of nanoscientific applications in modern life is swiftly in progress. Nanoscale innovation comes with the pressing need to provide citizens and learners with scientific knowledge for judging the societal impact of nanotechnology. In rising to the challenge, this paper reports the developmental phase of a research agenda concerned with building and investigating a virtual environment for communicating nano-ideas. Methods involved elucidating core nano-principles through two purposefully contrasting nano “risk” and “benefit” scenarios for incorporation into an immersive system. The authors implemented the resulting 3D virtual architecture through an exploration of citizens’ and school students’ interaction with the virtual nanoworld. Findings suggest that users’ interactive experiences of conducting the two tasks based on gestural interaction with the system serve as a cognitive gateway for engendering nano-related understanding underpinning perceived hopes and fears and as a stimulating pedagogical basis from which to teach complex science concepts.

Keywords: *Conceptual Learning, Immersive Virtual Environments, Interactive Gestures, Nanoscience and Nanotechnology Education, Public Understanding*

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THEORETICAL BACKGROUND AND RATIONALE

Importance of Nanotechnology and Nanoscience in Public Understanding and Education

Many scholars would agree that we are in the midst of a nano-revolution. From a scientific point-of-view, it is difficult to argue against the prediction that advances in nanotechnology will have a significant influence on the future of humanity. Technological progress at manipulating nanoworld objects, with sizes approximately one millionth that of a grain of salt, is underway culminating in the foreseeable production of nanomaterials, nanodevices, and nanobiopharmaceuticals (e.g. Teo & Sun, 2006). This rapid development places a huge demand on education-providers to deliver “nano-competencies”, whereupon since 2001, the U.S. government has invested \$6.5 billion in nanotechnology initiatives (Dyehouse, Diefes-Dux, Bennett, & Imbrie, 2008). In parallel, nanoscience is heralded as an opportunity to reform STEM education (Schank, Krajcik, & Yunker, 2007; Shabani, Massi, Zhai, Seal, & Cho, 2011).

While nanofever persists, Laherto (2012) and Lin, Lin, and Wu (2013) highlight the urgent need for nanoscience education to also consider public dimensions. Indeed, the societal impact of nanotechnology conjures up perceptions of fear and paranoia on one hand, and sheer wonder and excitement on the other. Nanoscience era role-players have a duty to empower citizens with a scientifically grounded basis for judging nanotechnology (e.g. Hingant & Albe, 2010). This emphasis is captured succinctly in Laherto's (2010) assertion that, “all citizens will soon need some kind of ‘nano-literacy’ in order to navigate important science-based issues related to their everyday lives and society” (p. 161). Gilbert and Lin (2013) have further unpacked this idea to reveal multi-level ideas underpinning nano-literacy.

Any nanoscience education agenda should also address citizens' reasoning, perceptions,

understanding, decisions and judgments surrounding nanotechnology. Recent literature (e.g. Besley, 2010) has highlighted the opportunity that a nanotechnology context offers for exploring how citizens evaluate risk with little or no knowledge grounding. Gilbert and Lin (2013) have suggested “risk” as a core theme in nano-education, whereupon it is essential for citizens to construct informed views about nano. Consequently, a research mission unfolds that seeks ways to provide citizens and learners with tools for developing knowledge to make scientific judgments about the potential benefits and risks of nano (e.g. Cobb & Macoubrie, 2004; Gilbert & Lin, 2013).

Educational Virtual Environments in the Learning and Acquirement of Scientific Knowledge

A review by Mikropoulos and Natsis (2011) has suggested that educational virtual environments can contribute to knowledge construction and attaining learning goals. Similarly, Richard, Tijou, Richard, and Ferrier (2006) have reported that virtual reality platforms can cultivate science knowledge-building processes, and allow exploration of difficult to access abstract science concepts. For example, Merchant, Goetz, Keeney-Kennicutt, Kwok, Cifuentes, and Davis (2012) showed that a 3D virtual environment enhanced learning of chemistry concepts. Students' interaction with the environment also influenced a range of perceptual and psychological characteristics. Work in physics has revealed improvements in students' conceptual understanding of electric fields following interaction with a virtual environment (Dede, Salzman, Loftin, & Ash, 2000).

Mikropoulos and Natsis (2011) reveal that few studies have investigated virtual environments that contain intuitive interaction, as well as users' attitudinal dimensions, and identify these as emerging trends in the field. Furthermore, the authors contend that, “systematic effort and more empirical studies are needed in order to show how the characteristics and features of educational virtual environments

can be pedagogically exploited” (p. 778). Earlier analysis by Dede (2009) echoes this view and calls for more studies on aligning the nature of the virtual environment with intended instructional design.

One central challenge of communicating nanoscience is the scale and symbolism of nano-phenomena (Batt, Waldron, & Broadwater, 2008). Another difficulty is the often counter-intuitive properties of objects at the nanoscale. One possible solution for providing access to this knowledge is to let users actively interact with virtual nano-objects in an immersive environment. Our hypothesis is that such interactions could unlock an understanding of nanoscale phenomena. Hence, we are currently conducting research with the objective to design and investigate virtual nanotechnology environments for learning. The present paper is concerned with Phase 1 and initial elements of Phase 2 of a three-phase research program:

Phase 1: To conceptualize and develop an interactive virtual reality architecture for communicating nano-related knowledge to public citizens and school learners;

Phase 2: To explore citizen and learner interaction with features of the virtual environment in building nanoscientific knowledge;

Phase 3: To investigate the implementation of components of the virtual reality architecture in real science classrooms and public contexts.

PURPOSE AND RESEARCH QUESTIONS

The present paper has a two-fold purpose. Firstly, we present the conceptualization and construction of a virtual environment to provide citizens and learners with scientific knowledge about nanotechnology. Secondly, we present a first exploratory investigation into how citizens and learners interact with the system. The paper poses the following three research questions:

- What fundamental nano-principles can serve as a meaningful knowledge base from which to interpret “risk” and “benefit” scenarios of nanotechnology for society?
- How can these scenarios be applied in the design and construction of an interactive virtual reality environment that affords communication of core nano-ideas?
- What does initial exploration of citizens’ and learners’ exposure to the virtual environment reveal about interaction and understanding afforded by the system?

METHODS

Defining Core Nano-Principles and Formulating the Applied Nanotechnology “Risk” and “Benefit” Scenarios

A content analysis of literature in this domain consisted of three steps. Firstly, we identified well-cited articles that explicitly aimed to define nanoscale ideas for understanding (e.g. Hingant & Albe, 2010; Stevens, Sutherland, & Krajcik, 2009; Tretter, Jones, Andre, Negishi, & Minogue, 2006; Wansom et al., 2009). Secondly, the textual descriptions of nanoscientific content knowledge were analyzed iteratively (e.g. Prieto, Watson, & Dillon, 1992) to develop common categories of nano-properties, which were then subsumed into umbrella nano-principles. Thirdly, we formulated two contrasting nanotechnology scenarios from the emergent nano-principles, one interpreted as a clear “benefit”, and another as a clear “risk”.

Application of the Nano-Principles and Scenarios in the Construction of a Virtual Environment

Subsequent to specifying relevant nano-principles and conceptualizing the nano-scenarios, we focused on constructing an interactive virtual environment to communicate the intended

nano-phenomena. As captured in Figure 1, the construction of the virtual environment is operationalized in terms of the indispensable union between four primary components: core *nano-concepts*, the “risk” and “benefit” *scenarios*, the nature and dimensions of users’ *interaction* afforded by the virtual environment, and the implemented *design features*.

Exploring Public Citizens’ and School Students’ Interaction with the Nano-Environment

Participants and Study Context

Collection of data from public citizens proceeded while the environment existed as a public exhibit at a science center in Sweden during 2013. With respect to the school students, three Swedish learners (two female and one male) aged 19 to 20, recently having completed upper secondary chemistry, participated in a case-based qualitative exploration of conceptual and interactive dynamics of the system (e.g. Harrison & Treagust, 2000). The three student participants provided informed consent to participate.

Data Collection

Public citizen data consisted of automatically logged anonymous information about visitors’

interactions with the system. Retrieved variables were interaction time, number of system activations, interactive grab time, and grab path-length. The student data consisted of a written pre- and posttest (e.g. Gardner, Jones, Taylor, Forrester, & Robertson, 2010; Jones, Andre, Superfine, & Taylor, 2003) and 4.3 hours of video-captured think-aloud sessions (e.g. Schönborn & Anderson, 2009). The written tests included nineteen closed items and five open questions (e.g. Dyehouse et al., 2008; Lee, Scheufele, & Lewenstein, 2005) that explored students’ knowledge of nanoscience and nanotechnology and their attitudes towards risks and benefits (e.g. Bainbridge, 2002; Cobb & Macoubrie, 2004; Lin et al., 2013; Siegrist, Keller, Kastenholz, Frey, & Weick, 2007). The closed items were statements that students responded to using a visual analogue scale (VAS) (Funke & Reips, 2012; Mytton & Rumbold, 2011) by marking an “X” on a 10-centimeter line ranging from 0 (“Disagree” or “Beneficial”) to 10 (“Agree” or “Risky”). The think-aloud sessions included semi-structured probes designed to induce students’ ideas and elaboration of the immersive virtual experience. Example probes included, “Why do you think that the nanotubes are bundling together?”, and “Can you relate some terms from science class to explain what you are seeing?”

Figure 1. The union between four indispensable elements that underpinned the conceptualization and construction of the immersive virtual reality architecture

Data Analysis

Analysis of logged time and frequency data obtained from public citizens as they progressed through the different screens of the virtual environment employed descriptive statistics. In addition, we analyzed logged data of the locations of users' heads and "grab" gestures while engaged with the two scenarios. The positional data from users while they viewed screens with static images and text constituted a baseline for comparison. An iterative, inductive and qualitative analysis of the video data utilized *Transana* software that enabled verbatim transcription and coding of the recorded data. The analysis operationalized potential cognitive processes associated with learning through interaction with the system in terms of: 1) connections between science concepts and interactive events, 2) science discovery within the virtual nanoworld, and 3) progressive refinement of hypotheses (Derry, 2007; Powell, Francisco, & Maher, 2003). Coding of time-stamped video episodes depicting critical events related to these aspects created a catalogue of student interactions and statements. We quantified students' unprompted interactions in the system in terms of frequency, duration, and relative proportion of the time spent in the scenarios. Lastly, we analyzed the video and written data for any relationships between students' conceptual understanding and attitudes to nanotechnology (Lin et al., 2013).

RESULTS AND DISCUSSION

What Fundamental Nano-Principles Can Serve as a Meaningful Knowledge Base from which to Interpret "Risk" and "Benefit" Scenarios of Nanotechnology for Society?

The "risk" scenario labeled *nano-toxicity* represents a potential nanotechnology hazard (cf. Siegrist et al., 2007) and is founded on the following core nanoscientific concepts and principles (Table 1): Nanotubes (often 1nm in

diameter but thousands of times longer) tend to aggregate into "bundles" due to "sticky" forces of adhesion arising from their extraordinarily high surface area-to-volume ratios. In addition, their high length-to-diameter ratios could be harmful in a similar fashion to the toxic effects of asbestos on the lungs.

The "benefit" scenario labeled *nano-therapy* represents an advantage of nanotechnology, and has the following core nanoscientific concepts and principles (Table 1) as its foundation: Artificial modification of nanotubes with a "coat" of molecules allows them to bind specifically to cancer cells. Nano-objects are in continuous random motion, and if introduced into the body, the coated nanotubes will eventually bind to targeted cancer tissues. Furthermore, nanotubes can act as "antennas" that absorb wavelengths of a particular infrared frequency, which is then disseminated as heat. Therefore, by applying infrared radiation, the heat generated via the bound nanotubes will destroy the cancerous tissue without harming the rest of the body.

We purposefully developed the scenarios at opposite ends of a risk-benefit continuum so that users could actively contrast them. As described in Table 1, users perform interaction tasks while engaging with the scenarios in the virtual environment. The images displayed in Table 1 are the "debriefing" images that follow each interactive scenario.

How can these Scenarios be Applied in the Design and Construction of an Interactive Virtual Reality Environment that Affords Communication of Core Nano-Ideas?

The constructed system utilizes 3D TV technology and motion tracking via a *Microsoft Kinect*. The depth camera detection of actions in a volume in front of the screen allows users to interact with stereo-rendered nano-objects using a defined hand gesture. Head tracking allows the virtual environment to provide users with a head-coupled perspective. Hence,

Table 1. Scientific concept examples and inferred nano-principles that informed the conceptualization of the nano-toxicity (“risk”) and nano-therapy (“benefit”) interactive task scenarios for incorporation in the virtual reality environment. Also shown are images implemented in the system to communicate the underlying implications of the nanoscale scenarios at more familiar scale levels (Embedded images 1-3 & 5 in the Table are under the Creative Commons Attribution License: image 1 from Materialscientist at en.wikipedia; image 2 from Mercer et al. (2011, 2010), Particle and Fibre Toxicology, 8(21), 3, and 7(28), 4; image 3 from Chikumaya at en.wikipedia; image 5 from Xiao et al. (2009), BMC Cancer, 9(351), 8. Image 6 © 2010, Joshua T. Robinson and Hongjie Dai, used with permission).

Scientific Concepts	Nano-Principles at the Nanoscale	“Risk” & “Benefit” Scenarios	Interactive Tasks and Intended Understanding Acquisition	“Scaling-up” of each Task Scenario from Nano to Micro to Macroscale
<p>Inter-molecular forces</p> <p>Length to Diameter ratio</p> <p>Relative size of objects</p>	<p>Nano-objects display unexpected behaviors</p> <p>Nanotubes tend to “stick” together to form bundles</p>	<p>Nano-toxicity</p>	<p>“Use the hand gesture to pull tubes apart or move tubes together, or see them aggregate by themselves.”</p> <p>“Pulling” the nanotubes apart and viewing them aggregate or “stick together” again is the basis for engendering conceptual understanding about the implications of such adhesion and high length-to-diameter ratio for potential nano-toxicity at the micro (e.g. cells) and macro (e.g. lungs) level.</p>
<p>Brownian motion</p> <p>Inter-molecular collisions</p> <p>Binding specificity</p>	<p>Nano-objects are in constant random motion</p> <p>Adhesive forces between nano-objects are dominant over other forces important at the macroscale.</p>	<p>Nano-therapy</p>	<p>[The user views modified nanotubes moving randomly, but binding to specific binding sites on the surface of a target cancer cell (see image to the right)]</p> <p>“Use the hand gesture to move tubes towards or away from the cell surface, or see them bind as they flow by.”</p> <p>[Later, the user presses a virtual button that ‘activates’ the infrared frequency to represent heating of the tubes].”</p> <p>Random and specific binding of modified nanotubes to cancer cells (and not healthy cells) is the basis for engendering conceptual understanding about the implications of targeted-nanotube delivery and thermal nanotherapy at the micro (e.g. cells) and macro (e.g. tumor) level.</p>

as per Slater and Wilbur (1997), the system is immersive by virtue of the surrounding nature of the wide-screen 3D display in combination with the matching between body movements and information generated on the display. Although not exploited in this study, the architecture also includes support for haptic hardware, planned for future investigations of the use of force feedback on users' interaction with the virtual nanoworld. Figure 2 depicts the immersive and interactive features of the virtual environment. Further technical information is available in Lundin Palmerius, Höst, and Schönborn (2012).

The resulting system consists of nine sequential "scenes". Users traverse scenes by pressing virtual "continue" or "back" buttons. The two interactive scenarios constitute scenes 5 and 8 in the sequence. Each scenario is introduced by a scene (4 and 7) that provides users with background information before interacting in each scenario, and follow-up scenes link the just-simulated scenario to objects at a more familiar scale (6 and 9, see Table 1). Remain-

ing scenes consist of an explanation of the 3D function (scene 1), instructions on performing the grab gesture (scene 2), and a prologue to the scenarios (scene 3).

What Does Initial Exploration of Citizens' and Learners' Exposure to the Virtual Environment Reveal About Interaction and Understanding Afforded by the System?

Exploring Public Citizens' Interaction with the Virtual Environment

Logged data from public visitors' real-time interaction with the system revealed that users activated the simulation sequence 1600 times. A total of 412 activations (approximating to individual users) corresponded to traversing the entire nine-step sequence. The average user-interaction time was 1.8 minutes, while traversing through all nine steps took 3.2 minutes on

Figure 2. Features of the interactive virtual nano-environment. A: The programmer of the virtual environment (co-author K.L.P.) demonstrates a Kinect depth image on the 3D TV obtained from a downward facing Kinect mounted on the ceiling (inset) that processes a "grab" hand gesture (see green circle arising from successful thumb and forefinger contact). The Kinect also tracks the position of the user's head (yellow) as well as engaged grabs in real-time. B: A screenshot demonstrating the grab gesture deployed to reach into the virtual scene to make contact (indicated by orange line) with a virtual nanotube. Making contact and moving, pulling or pushing the stereo 3D rendered nanotubes is the basis for performing the nano-toxicity and nano-therapy tasks (See Table 1).

average. Table 2 presents logged variables from the nano-toxicity and nano-therapy scenarios.

In addition to Table 2, the tracked data visualized public citizens’ spatial interaction with the system while interacting with the two scenarios, as displayed in Figure 3.

The data in Table 2 and Figure 3 delivered four assertions about citizens’ interaction. Firstly, the system promotes a highly interactive behavior via the grab gesture. In each nano-scenario, users spent more than half of their time attempting to interact with the virtual nano-objects (64% and 54% of time spent in

scenario, respectively). The active deployment of the grab gesture is visible by the grab positions depicted in Figure 3.

Secondly, the average grab path-length (the distance covered with one’s hand while a grab gesture remains engaged for greater than 1 second) also exemplifies users’ active movement of the virtual nanotubes (Table 2). The similar path lengths for the two scenarios indicate interactive consistency, while the grab location distribution in Figure 3 depicts interesting differences in interactive patterns for each scenario. While there was a regional clustering

Table 2. Logged data capturing dimensions of public citizens’ real-time interaction with the nanoworld in each of the nano-toxicity (“risk”) and nano-therapy (“benefit”) scenarios

Logged Variable	Nano-Toxicity (“Risk”) Interactive Scenario	Nano-Therapy (“Benefit”) Interactive Scenario
Total number of users activating the interactive scenario	816 sessions	448 sessions
Average time spent in interactive scenario	53.4 sec.	49.8 sec.
Average interactive grab time while in scenario	34.4 sec.	27.0 sec.
Average grab path-length while in scenario	33.0 cm	31.6 cm

Figure 3. The complete tracked data set of public citizens’ spatial interaction with the system in each of the nano-toxicity (A), and nano-therapy (B) scenarios visualized as normalized intensity plots. A control comparison is shown in (C) obtained from users’ viewing of a debriefing screen that contained only static images and text (this screen was presented subsequent to the state depicted in A). The data presents a top view looking down onto a plane that encapsulates the collection of all users’ head positions (green) relative to the locations of all users’ grab gestures deployed (red) in each scenario. Numerals on the axes represent displacement in meters.

of grabs apparent in the nano-toxicity scenario (Figure 3A, in red), there was a more elongated spread of grabs in the nano-therapy scenario (Figure 3B, in red). The latter indicates that users interacted with nanotubes positioned along the rendered cell surface (see fourth screenshot in Table 1), as shown by the approximate 60 cm distribution length. The right-tilted head movement coupled to this distribution also supports this observation.

Thirdly, the logged data suggests that users exploited the immersive qualities of the system. This assertion associates users' grabbing behavior and head movements with the degree of interaction provided by the system. Here, Figure 3A and 3B indicate that users move their heads while interacting with the virtual environment, as evidenced by the wide distribution of head positions. In comparison, the collected head positions in Figure 3C obtained when users viewed a screen comprising static images and text clearly demonstrates a much more confined head movement. This may indicate that interacting with the system provides users with a sense of presence. In support of this tentative interpretation, Slater, McCarthy, and Maringelli (1998) have reported a significant positive correlation between amount of body movement (including head motions) and sense of presence in a virtual environment. Furthermore, Hendrix and Barfield (1996) have shown that sense of presence was significantly higher when head-tracking provided a head-coupled perspective.

Fourthly, the average time that users spent at the exhibit mirrors typical reported values in the literature (cf. Sandifer, 2003). Once attracted to the system, users tended to spend considerable time engaged with it. Although public users were able to successfully interact with and navigate the system, almost half ceased interacting prior to the 'benefit scenario' (Table 2). Given that the environment aims to support public understanding of nano across a risk-benefit continuum, this drop-off in users (816 to 448) was unfortunate. From an exhibit point-of-view, further investigation is needed to determine whether the observation relates to

usability, design artifacts, or loss of interest in the topic or interaction.

Exploring School Students' Interaction with the Virtual Environment

Qualitative video analysis of students' interaction with the environment identified three salient themes, namely interactive styles, aspects of understanding, and pseudo-haptic dimensions. We first present datum examples obtained from each student's (pseudonyms used throughout) interactive session, and then interpret them in terms of the three themes.

The example in Figure 4 is a screenshot sequence (A-F) obtained from Drew's interaction during the nano-toxicity scenario, coupled to the following utterances:

I've just got to mention something (Figure 4A), that actually now I just discovered that uh... they [nanotubes] are pulling one another (Figure 4B), like here for example, I put it there (Figure 4C). I put them together, like one higher than the others (Figure 4D), and as times goes on, there, it comes down until it's at the, I don't know how to really call the point, but it keeps on moving until the... (Figure 4E) at the point that now they only wobble together and no moving up or down... (Figure 4F). (Scenario 1, 0:27:46 - 0:28:54)

Overall, Drew spent a total of 34.7 minutes in both scenarios. He spontaneously interacted on 38 separate occasions constituting a time of 8.5 minutes (25% of total time spent in the scenarios). The second example is from Harriet while in the nano-therapy scenario (Figure 5), that generated the following verbal exchange:

Interviewer: *Can you try that out? Take a hold of two nanotubes and see if you can get them to be attracted to one another. (Figure 5A)*

Harriet: *It doesn't want to come (Figure 5B). That's because of the extra molecules there, or? That it causes it not to be able to be attracted to*

Figure 4. Screenshot sequence (A – F) generated from the video of the interactive think-aloud session conducted with Drew while in the nano-toxicity scenario of the virtual nanoworld

Figure 5. Screenshots (A and B) generated from the video of the interactive think-aloud session conducted with Harriet while in the nano-therapy scenario of the virtual nanoworld

each other as easily as it did before. (Scenario 2, 0:06:22 - 0:07:12 [Tape2])

In total, Harriet spent 23.7 minutes in both scenarios. In contrast with Drew, despite repeated prompting, she only interacted spontaneously on six occasions for 1.3 minutes (5%). The third example (Figure 6) is from Nancy's interaction in the nano-therapy scenario in conjunction with the following excerpt:

They don't seem to be very strong attachments, because when there comes another tube and

pushes, [it] push[es] it, but then it releases and keeps moving. (Nancy, Scenario 2 0:09:13 - 0:09:26 [Tape 2])

Nancy performed six self-initiated interactions that comprised 2% (0.6 minutes) of a total of 33 minutes spent in both scenarios. The student data demonstrate different *interactive styles* associated with the environment. For instance, while Drew interacts spontaneously (Figure 4) in a spirit of self-discovery, Harriet and Nancy engage in limited grab gestures, indicating different approaches to interacting

Figure 6. A screenshot generated from the video of the interactive think-aloud session conducted with Nancy while in the nano-therapy scenario of the virtual nanoworld

with the virtual objects. To spontaneously demonstrate that nanotubes are “pulling one another” (Figure 4A and 4B), Drew manipulates one nanotube from a bundle (Figure 4C shows Drew’s deployment of the grab gesture to make contact with and move the nanotube of interest). He then places it slightly out of line and above the main bundle (Figure 4D). Drew then predicts that the nanotube will shift in position until it aligns with the bundle (as per Figure 4E). Finally, he notes that the nanotube will move in concert with the bundle (Figure 4F). This episode of discovery demonstrates Drew’s self-initiated interaction as a tool in engaging his conceptual understanding.

In contrast with Drew, Harriet interacted with the simulation quite differently. For example, although she successfully grasps two nanotubes and begins to move them in the region of one another (Figure 5A), she later loses ‘contact’ with the tubes (Figure 5B) and abandons the task. This episode indicates Harriet’s potential lack of confidence in exploiting the interactivity to solve the task, as well as the necessity of the interviewer to prompt Harriet’s interaction forward. Overall, the data revealed two distinct interaction patterns: either *self-initiated and exploratory*, or *tentative* that

requires *continuous prompting*. Further work is required to investigate how these styles relate to individual modes of learning (Hauptman & Cohen, 2011; Wang, 1995).

The analysis also suggests that the interactive environment can support students’ conceptual reasoning without engaging formal scientific terminology. For example, Drew’s placement of a nanotube a short distance away from a bundle indicates the understanding that the distance affects the attractive force (Figure 4C). Drew also notices that the nanotubes will move to form bundles that maximize surface area contact (Figures 4D – F) without expressing formal scientific terminology to convey the complex idea that, “...as times goes on, there, it [nanotube] comes down” (Figure 4D). Drew’s developed understanding of this nano-phenomenon relates to his interactive experience, and an interesting observation by Author J.F. was that although Drew was weaker on traditional classroom assessment, the simulation seemed to unlock an alternative learning situation. Drew’s interaction supports Dede’s (2009) postulate that positive cognitive engagement in a virtual interaction may trigger the “release of trapped intelligence”.

With respect to other conceptual aspects, while in the nano-therapy scenario, Harriet tries to place two nanotubes close to one another and utters, *"It doesn't want to come (Figure 5B). That's because of the extra molecules there or? That it causes it not to be able to be attracted to each other as easily as it did before."* Although Harriet loses contact with the tubes, she alludes to an understanding of relative forces. While Nancy's interactive session exposed a single formal science term (London forces), her suggestions that, *"they don't seem to be very strong attachments ... (Figure 6)"*, and, *"another tube [comes] and pushes, [it] push[es] it, but then it releases"*, intimates a conceptual understanding of the relative strength and non-permanence of intermolecular interactions. Concerning conceptual shift after interaction with the system, Nancy's respective responses to the written pre-/posttest item, "What do the terms "nanoscience" and "nanotechnology" mean to you? Please give as much detail as possible" were as follows:

Nanoscience and nanotechnology to me mean science and technology on a small scale level, where only small particles are used. It also mean[s] science and technology that in everyday life is "invisible" but important. (Nancy, Pretest)

It means technology and science on an atomic and molecular level, what has applications within many different areas such as medicine. It also means science where single atoms and molecules are put together to get a specific 'behaviour.' (Nancy, Posttest)

The data above suggests a shift from a conception of nano as "small scale" and "invisible" to a more sophisticated understanding that includes manipulation of atoms and molecules in order to achieve a specific property or behavioral manifestation. Hence, interacting with the environment could allow for meaning-making not necessarily exposed as formal scientific terminology but through an alternative intuitive process (cf. Richard, et al.,

2006). This could parallel Dede's (2009) notion that changing "one's frame of reference" (in this case clasping and moving nanotubes) could be "a powerful means of understanding a complex phenomenon" (p. 66). In summary, the conceptual dimensions that emerged suggest that the virtual environment could serve as an alternative vehicle for constructing understanding via a natural interface (Richard et al., 2006), as well as through off-loading and re-representation opportunities (Scaife & Rogers, 1996) embodied in the interaction (Wilson 2002).

Although students did not experience direct tactile sensory input, the virtual environment induced interesting force-related experiences. For example, as shown in Figure 4B, Drew forms a fist and gestures the notion of pulling an object in combination with his utterance that, *"nanotubes are pulling one another."* In addition, Nancy attributes the notion of force strength when suggesting that, *"they don't seem to be very strong attachments (Figure 5)"*. This finding raises the exciting possibility of a pseudo-haptic transfer of ideas about forces without any force feedback technology (e.g. Lecuyer, Coquillart, Kheddar, Richard, & Coiffet, 2000).

With respect to students' attitudes towards the benefits and risks of nanotechnology, written VAS responses for three attitudinal constructs (0=Disagree to 10=Agree or 0=Beneficial to 10=Risky) invoked differing pre- and post-interaction rankings (Table 3). Attention in the analysis was on rankings that changed in value greater than three units or shifted from one pole to the other.

The constructs specifically concerned with nanotubes revealed shifts for all three students from more beneficial towards more risky (Table 3). The first of these constructs links strongly to the nano-toxicity scenario (cf. Table 1). No numerical shift towards a more beneficial view of nanotechnological cancer treatment requires future investigation since it maps to the nano-therapy scenario (cf. Table 1). Unlike the other two students, Harriet shifts her quantitative attitude ratings across the scale midpoint in all three constructs from viewing nano as beneficial

Table 3. Results of selected pre- and post-interaction attitudinal constructs after students' interaction with the simulation. italicized rankings depict ranking shifts > 3 scale units

Attitudinal Construct	Student Rankings					
	Drew		Nancy		Harriet	
	Pre	Post	Pre	Post	Pre	Post
"Nanotechnology will not harm our health" (from Lin et al. 2013)	4.7	4.3	6.9	7.2	5.5	0.4
"How beneficial or risky do you consider industrial manufacturing of nanotubes to be for Swedish society as a whole?" (from Siegrist et al. 2007)	1.7	4.9	1.7	2.7	4.1	8.4
"How beneficial or risky do you consider cancer treatment with nanotubes/nanocapsules to be for Swedish society as a whole?" (from Siegrist et al. 2007)	0.1	1.2	1.2	1.8	1.3	6.3

to risky. The video and written pre-/posttest data revealed qualitative aspects of students' benefit-related attitudes to nanotechnology. For instance, Drew uttered the following during his interaction with the environment:

I: *Do you feel that this interaction has affected your viewpoint in any way?*

Drew: *Yes, it has.*

I: *Yeah, in what way?*

Drew: *... Well... I didn't have the knowledge... about cancer and nanotubes and uh... modification of carbon nanotubes and how that... really would... influence... for example, my health...*

I: *And... did you change your point of view on, as if it were a beneficial thing or a risk?*

Drew: *Uh... In both ways because... now I have the knowledge that... what are the dangers of the nanotubes and what are the benefits of the nanotubes. Through the nanotubes... our health will be improved but through the nanotubes, at the same time... our health status may decrease, become affected. Yeah.*

I: *And do you think that has affected how you view nanotechnology as favorable or not favorable?*

Drew: *Well I'm at the middle level, it's favorable and it's not favorable. Because uh... yeah it's both good and bad. It depends on how you look at it. (Drew 1:43:53 - 1:46:33).*

The excerpt above reveals a benefit perspective infused with Drew's attitude to nano. Furthermore, he associates a conceptual understanding aspect by first saying that he has acquired the knowledge with which to interpret the potential benefit and risk. Secondly, he posits that this newly acquired knowledge allows him to construct his stance at a mid-point between "good" and "bad". In response to the written pre-/posttest item, "Describe one way nanotechnology may benefit society/humankind", Harriet penned the following respective responses:

Medical wise many cures can hopefully be found. They can be very specific and hopefully side effects can be reduced. (Harriet, Pretest)

Modified nanotubes may be used for curing cancer. These modified nanotubes are attracted to cancer affected cells, the molecules on the nanotubes then bond to the cell. The nanotubes then absorb infrared radiation and then converts it to energy being released... (Harriet, Posttest)

The first datum demonstrates that Harriet exposes a general idea of the possible medical benefit of nanotechnology prior to interaction. However, following interaction, Harriet expresses a more specific response with respect to potential cancer treatment. Similar to Drew, her

answer also exhibits conceptual understanding, in this case related to the energy conversion in this nanotechnological application. Overall, these qualitative data indicate a strong interaction between conceptual understanding and attitudes to nano (cf. Lin et al., 2013), dimensions rarely probed amongst secondary students in this field.

CONCLUSION AND IMPLICATIONS

This paper has reported the conceptualization, construction and implementation of an interactive virtual environment for engendering understanding of core principles of nano among citizens and students. A set of core nano-principles were identified that can serve as a knowledge base in the judgment of risks and benefits of nano. Potential risks and benefits were brought into focus by specifying two scenarios involving nano-therapy (nanotubes in cancer treatment) and nano-toxicity (respiratory tract damage from nanotube inhalation), respectively. Application of the scenarios in an immersive 3D environment communicates the identified core nano-ideas by allowing users to interact with nano-objects through gestures. Initial exploratory data collected from citizens' and learners' exposure to the virtual environment revealed aspects of user interaction afforded by the system. Real-time data from citizens' interaction with the environment confirms that the design of the system promotes a highly interactive experience, and the study provides early insight into how students' interaction may provide an alternative platform for learning complex science concepts.

Our future research will further investigate what *conceptual*, *interactive* and *design* artifacts of the virtual system can be applied to real science classrooms with the parallel goal to scaffold nano-literacy at large. This will also include the ongoing development and validation of instruments to generate data about knowledge and attitudes to nano before and after exposure to any intervention (e.g. Dyehouse et al., 2008),

as well as investigating usability parameters. We continue to pursue this urgently needed research to further uncover *how* interaction with virtual systems (e.g. Dede, 2009; Höst, Schönborn, & Lundin Palmerius, 2013) relate to cognitive and conceptual changes, and what artifacts promote these transitions.

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