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Enabling people who are blind to experience science inquiry learning through sound-based mediation

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Abstract

This paper addresses a central need among people who are blind, access to inquiry-based science learning materials, which are addressed by few other learning environments that use assistive technologies. In this study, we investigated ways in which learning environments based on sound mediation can support science learning by blind people. We used NetLogo, a multi-agent programmable modeling environment that is widely used for learning about complex systems. In order to provide blind people with access to such models, we used a component that supports sound-based mediation. The sound-based mediation provided real-time information regarding objects' speed, location, and interactions with other objects. We examined blind people's learning about a chemical system of contained gas particles. The study employs a pre-test intervention–post-test design. Four adults participated individually in the study. They achieved most referent-representation connections; their scientific conceptual knowledge became more specific and aligned with scientific knowledge; and their systems reasoning showed greater discrimination and relation between components. Discussion addresses learning with sound-based mediation in broader terms and suggests further research into the potential of this unique type of low-cost learning environment to assist blind people in their science learning.

Keywords

blindness, human–computer interaction, learning environments, simulations, special education.

Introduction

In exploratory learning of science, people who are blind need to employ compensatory channels to access visual information. One way of doing this is to make use of auditory information. To this end, we have developed 'Listening to Complexity'[1] (L2C), a sound-based representation to support learning about complex systems. The sound-based mediation provides real-time information regarding objects' speed, location, and interactions with other objects. We investigate inquiry learning by people who are blind through a structured exploration of a computer model based on auditory representations. The learning activity focuses on a system of contained gas particles, a core topic in chemistry education.

The study is based on the assumption that providing appropriate information through compensatory sensory channels may contribute to learning by students who are blind. The short-term goal of this research is to investigate ways in which learning environments based on sound mediation can support the learning of chemistry by people who are blind. The long-term goal is to support students who are blind by providing equal

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access to science, technology, engineering, and mathematics (STEM) learning, allowing them to interact with exploratory materials, independently collect data, and function as participants and contributors in a research group.

Literature review

This literature review features science education and auditory information technologies for people who are blind and who are understanding and learning about complex systems and chemistry through a complexity perspective

Science education for students who are blind

In many countries around the world, specifically in Europe, the USA, and Israel, students who are blind have been integrated into public schools for over 60 years and are required to complete the same curriculum and examinations as sighted students. However, as many STEM education resources are based on the visual mode, they are unable to access information first hand (Beck-Winchatz & Riccobono 2008). Several manuals have been written on how to teach science to students who are blind and to those who are visually impaired (Hadary & Cohen 1978; Willoughby & Duffy 1989; Kumar *et al*. 2001). Few learning environments based on assistive technologies have been created to support science learning, but one example is the use of a force-feedback mouse to study physics (Farrell *et al*. 2001; Wies *et al*. 2001). Going beyond existing technologies, in the current research, the user interacts with *dynamic and multiple* objects that are computed in real time, providing a sense of reality while learning about complex scientific phenomena.

Auditory information technologies for people who are blind

People who are blind learn by gathering information with perceptual and conceptual tools. The L2C environment harnesses the auditory mode to transmit dynamic complex information through use of technologies. The choice of an auditory display results from three considerations: (1) the auditory mode transmits information that changes both in space and time, similar to the visual mode and different from the haptic mode; (2) the auditory mode easily interfaces with large bandwidths at fine frequency-discrimination and intensity-discrimination thresholds (Capelle *et al*. 1998); and (3) the auditory system is capable of dealing with complex and rapidly changing sound patterns (Hirsh 1988).

Sonification is the presentation of information using non-speech sound (Kramer 1994). Nees and Walker (2009) present a classification of auditory sonified computer-based representations: (a) alerts; (b) object and status indicators, auditory menus; (c) data representation; (d) spatial audio displays; (e) soundscapes and background sound; and (f) arts and entertainment. Classes (a) through (d) are used in the L2C environment. Research into the impact of sound components on auditory perception has shown that increasing the number of audio channels beyond three causes degradation in comprehension (Stifelman 1994) and that a greater frequency separation between sound streams results in better stream segregation (Bregman 1990). Over the years, several auditory technologies have been developed for people who are blind. Some examples from the field of orientation and mobility include Sonicguide (Warren & Strelow 1985); Kaspa (Easton & Bentzen 1999), Palmsonar (Takes Corporation 2007), Talking Signs (Crandall *et al*. 1995); activated audio beacon using cellphone technology (Landau *et al*. 2005); vOICe (Meijer 1992), virtual sound display (Loomis *et al*. 2007), sound-based virtual environment systems (Sánchez *et al*. 2008), auditory graphs (Walker & Mauney 2010) and virtual environments for spatial learning based on audio and haptic feedback (Lahav & Mioduser 2004; Lahav *et al*. 2008).

The few systems developed to support STEM education among students who are blind have been based on audio and 2D tactile materials for learning mathematical and science diagrams. One example is the Line Graphs technology, which employs auditory and haptic feedback, and is geared to learning mathematics (Ramloll *et al*. 2000).

Understanding and learning about complex systems

Complex systems are composed of many elements, which interact among themselves and self-organize in coherent global patterns (Bar-Yam 1997). The field of complex systems contributes to our understanding of a wide range of systemic phenomena (Nicolis & Prigogine 1989; Barabasi & Bonabeau 2003; Turchin 2003). It provides a framework for representing and comprehending the structure and dynamics of systems, focusing on generating global patterns from local behaviours and interactions.

Complex systems challenge our understanding. Several biases frequently sway people's reasoning about systems, such as assuming central control (Resnick 1994), assigning the behaviour of one level to another, presuming deterministic rather than stochastic behaviours (Wilensky & Resnick 1999), focusing on the system's structure at the expense of function and mechanism (Hmelo-Silver & Pfeffer 2004), and tending to view causal relations as a consecutive chain of causes and effects rather than as parallel concurrent interactions (Chi 2005). Several innovative learning activities have been designed to help people overcome these biases and understand complex systems, such as constructing and exploring computer models (Wilensky & Resnick 1999; Ioannidou *et al*. 2003; Levy & Wilensky 2009a,b) and participating in role-playing simulations (Colella 2000; Klopfer *et al*. 2005). In this study, systems reasoning is examined with a focus on distinguishing and connecting levels, and understanding stochastic behaviours and interactions.

Understanding chemistry through a complexity perspective

In chemistry education, one of the central frameworks presented by Johnstone (1993) is that a well-developed understanding of a chemical system relates three forms of description, which map nicely onto a complexity perspective: the submicroscopic level, the macroscopic level, and representations. Previous research describes several challenges in understanding chemical systems, particularly with respect to gases, the focus of this research. These include the lack of a particulate view of matter, assigning macro-level behaviours to gas particles (Nussbaum 1985) and not considering random particle motion in a gas or liquid (Novick & Nussbaum 1978; Westbrook & Marek 1991). Most of these problems result from a failure to distinguish among levels, the particle level, and that of the whole group of many particles. The challenge of understanding this distinction, as well as the idea of randomness, is directly addressed in this study. In spite of these impediments to understanding chemistry, well-designed educational interventions that are based upon the use of computer-based models with multiple and bridged representations, similar to those used in this study, have been shown to circumvent the above-described difficulties (Kozma 2000; van der Meij & de Jong 2006; Levy & Wilensky 2009b). The present research examines conceptual understanding of the scientific topic, the particulate nature of matter, and several physical principles related to the behaviours and interactions of gas particles.

The L2C learning environment

The L2C computer-assisted learning environment supports students who are blind in an exploration of simulated chemical systems using a sound-based representation. L2C includes an agent-based computer model, a recorded voice guide, and the interviewer.

The computer model

Agent-based modeling is a relatively new computational modeling paradigm, which simulates complex dynamic systems by simulating each of their many autonomous and interacting elements. NetLogo (Wilensky 1999a) is one such modeling environment. NetLogo models are used in the GasLab (Wilensky 1999b) and Connected Chemistry (Levy & Wilensky 2009a) curricula. These agent-based computer models enable learning about chemical systems at both the observable macro- and molecular micro-levels. With Connected Chemistry, one learns the gas laws – how observable gas properties change under various conditions, e.g. how inflating a bicycle tire increases its internal pressure; kinetic molecular theory (KMT) – motion, force, and energy of invisible gas particles, and how KMT may generate observable phenomena. Research with sighted participants using this approach has revealed significant learning gains in understanding both the behaviours of gas particles and how these relate to observable phenomena (Levy & Wilensky 2009b).

The activity in this study is based on the first module in Connected Chemistry and centred on the phenomenon of inflating a bicycle tire. It consisted of interaction with a real bicycle tire, training with the individual sounds, and a guided exploration of the model. In order to make the environment accessible to people who are blind, variables, locations, and events related to both a single particle and to all the particles together were represented with sound. The sound at this stage of research

Table 1. Comparison of sonified and visual representations in the L2C computer model.

	Events, location, variables	Visual representation	Sonified representation (MIDI based)
Events	Collision among particles from the perspective of one focus particle	Two dots move in straight lines, meet at one location, and move apart in straight lines	Cowbell sound upon collision at one pitch
	A particle hitting the wall of the container (a square) from the perspective of one focus particle	One dot hits the wall at an angle, the wall become lighter at the point of contact, and the dot bounces off the wall	Clavi sound upon hitting a wall
	Entry of new particles in the container	A semi-circle spread of dots starts from the box's opening	Gong sound at constant pitch
Location	The location of a focus particle as it moves through the container	Full information is provided by placing a halo on the focus particle or have it leave a trail	Partial information is provided by wall hitting events where each of four walls has a different pitch
Variable	Speed of one focus particle	The dot is seen as moving faster or slower, changes colour within three speed ranges (blue – slow, green – medium, red – fast)	Oboe sound with pitch a linear function of particle speed

MIDI, Musical Instrument Digital Interface.

is in mono audio format. Table 1 shows the sound-based components of the model and compares them with the visual information available to sighted individuals with the original model. These sounds can be heard singly or concurrently (first listening to a single particle's properties, events and location and then attending to these features when the bicycle tire is inflated). It is possible to view and listen to a sample at http://www.youtube.com/watch?v=c0EdRKdjfgk. Figure 1 displays part of the model's interface: a number of dots (particles) inside a container (bicycle tire with a valve) that can be inflated.

Several issues were considered when designing the sound-based data representations. These included mapping (which sound attributes are used), polarity (direction of change in the sound attribute), and scaling (how much change in the sound is needed to convey a given change in the referent); the structure of the data generating the sound [noisy or random (in the current study)]; constant, linearly ascending, discontinuous, or interrupted (Pauletto & Hunt 2009) and detectability and discriminability, interactivity, individual differences, training, concurrent sounds, and delivery of audio through hardware and software (Nees & Walker 2009).

Recorded voice guide

Learning through exploring the model is supported with recorded instructions, explanations, and questions.

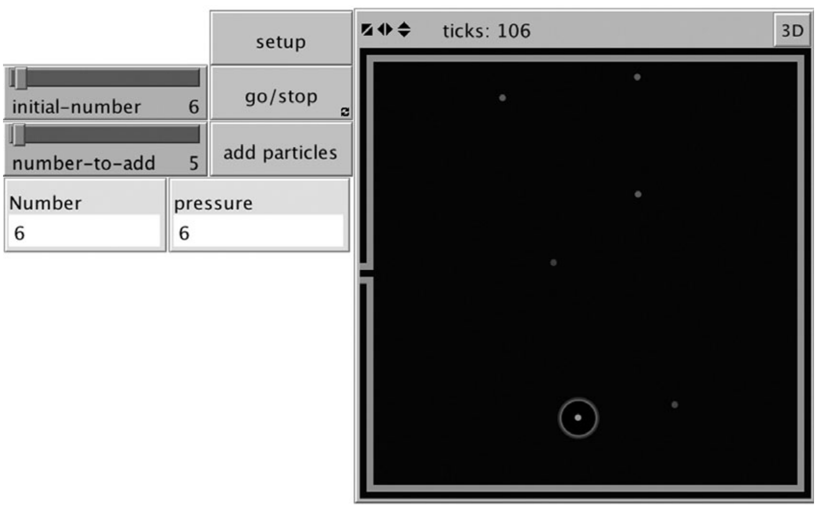

Fig 1 NetLogo sonified *model* of gas particles in a container interface.

Most of the questions are structured on the Predict–Observe–Explain scheme of inquiry learning in science (White & Gunstone 1992). A detailed description of the activity is provided in Table 2.

The interviewer
In these interactions, the interviewer operated the model; however, in future designs, the user will have control, using the keyboard.

There were two main research questions:

1 What scientific conceptual knowledge is learned as a result of interaction with the L2C environment by people who are blind?
2 What systems reasoning is learned as a result of interaction with the L2C environment by people who are blind?

Method

Participants

Four participants were recruited by snowball sampling. They were adult English speakers who were totally blind, their onset of blindness was at least 2 years prior to the experimental period, and they were computer users. The participants' age range was 40–57 years. Three of the participants were male and one female. All were late blind and had used computers for over 20 years. They had learned science, specifically phases of matter and KMT, in middle school and high school, and some in college. None had used computer-based models.

The target population ranges from seventh grade through undergraduate level. The discrepancy in age of this study's participants with respect to the target population arises for two reasons. First, since this type of environment presents a new approach to teaching science, we wanted to explore learning interactions without the shadow of recent negative experiences in learning science that may have developed in the past and which could cause the participants to reject learning within this environment. Second, we chose participants who were experienced computer users and who could provide a broad range of feedback, helping us to improve the learning environment. This sample is small due to the exploratory nature of this study.

Variables

Two dependent variables were defined: *scientific conceptual knowledge* – understanding of the physical principles governing the particles' behaviour as single objects (KMT) or as a group of particles (gas laws), based on accepted science literature and science education research; and *systems reasoning* – general structure of explanations with respect to stochastic interactions between objects, distinction, and relation between submicro- and macro-levels.

Data collection instruments

A research protocol
This protocol is based on the first activity in Connected Chemistry and focuses on the phenomenon of inflating a bicycle tire. It relates to the way the learning activity is conducted and is composed of three sections (Table 2): (1) physical interaction with the bicycle tire; (2) interacting with the submicro-level in the model; and (3) interacting with both the submicro- and macro-levels in the model. The three sections comprised a sequence of tasks and included 20 open questions before and after each task.

A background questionnaire
The questionnaire comprised 17 questions establishing personal information about the participants and their background in science education and computer use.

A pre- and post-test
A content knowledge questionnaire assessed the learners' understanding of the gas laws and KMT, concepts addressed by L2C. The questionnaires were identical and included three open questions and ten multiple-choice questions. The open questions required modeling of a system similar to that found in the experimental setting, The multiple-choice questions were a subset of those used in previous large-scale research on students' learning of similar topics (Levy & Wilensky 2009b), in which issues of validity were addressed through a systematic analysis and mapping between the curriculum and the questionnaire, employing several items previously used in other studies and several rounds of review by two research teams. All the visual images in the pre- and post-test were recreated as tactile images with special dimensional paint. The image size was

Table 2. Design of the activity in terms of three main sections, the learning goals, and the guiding questions.

Section	Sub-section: phenomenon and concepts	Questions directing inquiry
1: Direct manipulation of physical phenomenon	Pumping up a bicycle tire: physical experience, pressure changes	1. Describe the important differences between an inflated and a deflated tire. 2. What evidence would support the argument that there is gas inside the balloon or the bicycle tire?
2: Interaction with model of simulated dynamics of micro-level particles	Collisions of a single particle with container walls: random straight-line motion, hitting wall changes direction	3. What pattern do you think describes how a particle moves through the box, and more specifically – when it hits the walls? 4. (not used) 5. Based on what you have heard, describe how the particle moves through the box.
	Speed of a single particle: changes at random intervals	6. What do you think causes the change in speed? 7. How do you know?
	Particle collisions of a single particle	8. Can you find a pattern that describes how often a single particle collides with other particles? 9. Explain your answer.
	Particle collisions and speed of a single particle: collisions at random intervals, speed change upon collision	10. What do you predict about the relationship between a particle's collisions with other particles and its speed? 11. What relationship can you conclude between how the particle speed changes and its collisions with other particles? 12. What relationship can you conclude between how the particle speed changes and its collisions with other particles?
	Wall collisions and speed of a single particle: hitting a wall does not change speed but changes direction	13. What do you predict about the relationship between a particle's wall hits and its speed? 14. What do you conclude regarding how wall hits and speed changes relate? 15. What do you conclude regarding how wall hits and speed changes relate?
3: Interaction with model of simulated dynamics of both macro phenomena and micro-level particles	Particle collisions of a single particle upon adding particles: increase in rate	16. Predict how adding particles into the container may impact a single particle's collisions with other particles. 17. How do the particle's collisions with other particles change when there are more particles in the box?
	Speed of a single particle upon adding particles: rate of speed changes increases with gas density	18. Predict how adding particles into the container may impact a single particle's speed. 19. How does the particle's speed change when there are more particles in the box?
	Transfer question: changing volume: decreased volume results in greater density and rate of speed changes, same rate of wall hits and average speed	20. What will happen if the container is smaller for the same number of particles?

between 5 and 8 cm, a size that can be explored with two hands at the same time.

Observation

Participants' activity was video-recorded.

The research protocol's guiding instructions and the activity questions were recorded by an English speaker and were made available to the participants as an audio output.

Procedure

All participants worked individually with the interviewer. The design is a pre-test, intervention, and post-test. When using the model, each participant sat at a desk and received the auditory information through the computer's speakers. The session was carried out in four stages. In the first stage, the study was introduced, consent was obtained, and background information was recorded (15–20 min). The second stage entailed administering the pre-test questionnaire (15–20 min). The third stage was the intervention: (1) the participants manipulated and inflated a physical bicycle tire and answered several questions about this experience; (2) assisted by the interviewer operating the model and by recorded guiding instructions and questions, the participants interacted with the model to learn about a particle; and (3) similarly, they then used the model to learn about air pumping (45–90 min). The fourth stage involved administering a post-test (15–20 min). No feedback was provided on performance at any stage. Following the post-test, the subjects were asked to comment on their learning experience and provide ideas for improvements. The sessions (questionnaires and learning activities) lasted about 1.5–2.5 h, were video-recorded, and were later transcribed and analysed.

Data analysis

Data analyses were based on participants' verbal answers to the questions presented in the questionnaires and activities. These answers were coded for the dependent variables: scientific conceptual knowledge and systems reasoning.

With respect to scientific conceptual knowledge, questions were coded based on previous coding of the same questions (Levy & Wilensky 2009b). Closed questions were coded as correct or incorrect, and open questions were coded for the relevant correct scientific principles they included. The two authors independently coded all the questions. Inter-judge reliability was 90%. Alternative conceptions or incorrect scientific principles were analysed separately for emergent explanatory categories. The participants' answers during the activity were charted with respect to the distinct stages in the activity, so that possible associations between the structure of the learning environment and the kind of conceptual understanding elicited and learned could be surmised.

For systems reasoning, the open questions were coded based on three central components (Wilensky & Resnick 1999; Jacobson 2001) that described the structure of the explanation: whether the system was described at the submicro-level (particles, e.g. '. . . when particles collide they slow down'), the macro-level (system-wide properties, e.g. 'when I push down on it [the bicycle tire], it takes more weight to push it down and then flatten it'), or both (e.g. 'it will slow down the particles' speed because of the pressure'; including interactions among submicro-level objects (e.g. 'I think that when they [the particles] collide, the speed increases'); expressing the stochastic nature of the particles' behaviour (event probabilities, e.g. 'and it [the particle] is moving randomly within the box').

For the pre- and post-test, descriptive statistics were compared, and progressions of frequencies were computed and related to the activity.

Results

The findings from this study are presented with respect to the research questions.

> Research Question One: What scientific conceptual knowledge is learned as a result of interaction with the L2C environment among people who are blind?

It was found that the participants' total score for the pre-test and post-test questionnaires rose from 37% (SD = 10%) to 62% (SD = 14%). A more discriminate analysis of individual dimensions shows the following. Initial descriptions of the bicycle tire were in terms of its observable machinery but not the invisible air particles; prior knowledge about gas particles was that the rate of collisions among particles depends on their density and that particles' collisions result in speed and direction change. The main learning gain (three out of four participants) was in understanding of gas particles as randomly distributed in the container. Describing the model's target – inflating a bicycle tire – as including air (two out of four), indicated a shift to a combined view of macro- and submicro-levels. One concept the participants did not learn is that collisions among particles and with the wall of a container are distinct in terms of change in speed. In parallel, two out of four participants described the particles' behaviour both in physical terms (for collisions, they described the particles' changing direction and speed) and intentional terms (for diffusion, they portrayed particles as 'wishing' to move into empty spaces). One participant understood the system as physical from the start, and one participant shifted from an intentional to a physical description.

Each of the participants' responses during the activity was coded for the expressed scientific concepts, attending to the submicro-level rules. Prediction questions are not included in the analyses, as they do not reflect learning. Figure 2 describes the number of participants who expressed each of these principles for the activity's successive questions.

Activity questions (Table 2) regarding which three or four participants expressed a given principle are noted. This analysis is based on fundamental science literature and science education research.

Gas is made up of particles

Once the model of gas particles in a box was introduced (Q3), all participants began to describe the system in terms of particles, and continued to do so throughout.

Particles move in straight lines

This principle was articulated frequently for Q5 and Q15. Both relate to a particle hitting four different walls of the container, from which all the participants surmised that particles bounce between the walls and expressed the principle of straight-line motion.

Particles change direction upon hitting a wall

All participants articulated this principle for Q5, part of an activity that involved a particle hitting the walls.

Particles change direction upon colliding with another particle

This principle was not mentioned by the participants.

Particles do not change speed upon hitting a wall

In the post-test, no learning of this principle was observed. However, three out of four participants articulated it for Q14 during an activity that highlighted a particle's speed and wall hits.

Particles change speed upon colliding with another particle

All participants articulated this principle; it was understood from the start and was frequently expressed for Q12, which centred on a particle's speed and its collisions with particles.

Particles move about randomly

In moving from pre-test to post-test, all the participants expressed a better understanding of the random spatial distribution of particles. This principle was articulated at high frequencies for Q5, Q8, and Q14, which relate to distinct phenomena: a particle hitting the walls, collisions among particles, and relating speed and wall hits.

As mentioned above, during the pre-test, post-test, and activities, the participants expressed ideas that were related to the activity's learning goals. In addition, they expressed three ideas that related to the particles' direction of motion, an aspect that was not represented in the model. For example, the sound of a particle hitting each of the four walls of the container provided only partial information regarding location. However, the participants went beyond this information surmising a full path of motion: a 'ricocheting' or 'zigzagging' motion across the space of the container. Finally, some of the participants perceived an 'average speed' of the particle and even connected it to its actual value.

Besides the correct ideas presented above, the participants expressed alternative conceptions, which are scientifically incorrect ideas. The alternative conceptions included five groups: (1) walls absorb energy from particles, provided four times by all four participants; (2) walls transfer energy to particles, provided four times by three of the participants; (3) collisions take up energy, provided six times by all four participants; (4) collisions impart energy unto particles, provided twice by one participant; and (5) additional ideas (provided six times). The number of alternative ideas expressed

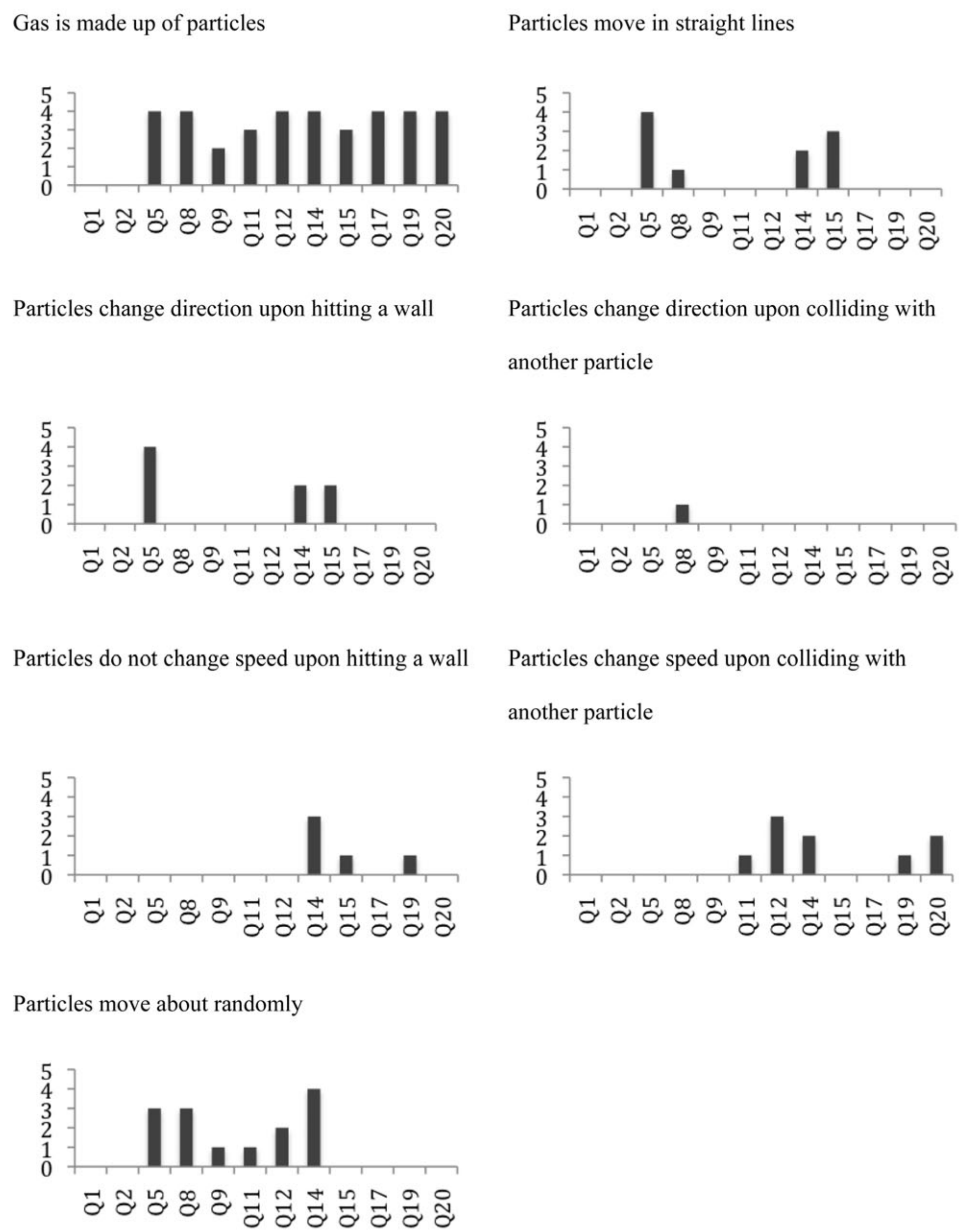

Fig 2 Progression of expressions of correct understanding of the micro-level rules regarding gas particles' behaviour. *X*-axis is the question number in the activity. *Y*-axis is the level of the answer as described in the text.

throughout the activity is presented in Fig 3. Conflicting alternative conceptions were provided by three participants: two described both (1) and (2); one described both (3) and (4).

To conclude, participants varied with respect to expressing alternative, rather than correct, ideas. Alternative ideas were expressed more frequently in the first half of the activity (14 times) than in the second half (eight times), portraying an increased understanding of the system under study. Most alternative ideas involved energy transfer relationships. More frequent were ideas of energy absorption through collisions. These ideas were not consistent.

Research Question Two: What systems reasoning is learned as a result of interaction with the L2C environment by people who are blind?

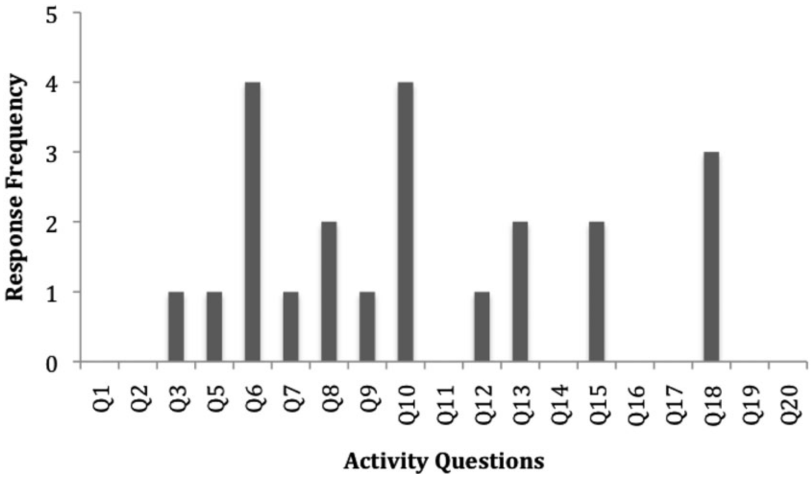

Fig 3 Number of alternative ideas expressed by each participant throughout the activity.

The following graphs present progressions for each of the participants (Fig 4). Participants' reasoning in terms of *levels* is described as providing no answer (1 in the graph), focusing on the macro-level (2), the submicro-level (3), or relating the two (4). One can observe clear distinctions between the three sections of the activity (Table 2). Section 1 elicits descriptions mainly at the macro-level. In Section 2, most of the responses highlight the submicro-level. Section 3 draws several responses that connect the levels in the system.

Figure 5 presents the number of participants who described *interactions* at the submicro-level. No interactions were described in Section 1. In Section 2, most of the participants described such interactions. In Section 3, the number of participants who included interactions in their description increased.

The third component, *stochastic* behaviour of the particles, is not presented as it is identical to that described in the previous section regarding the randomness of particles' motion.

To conclude the section on understanding as framed by a complex systems approach, the participants' answers corresponded with the structure of the activity, shifting from macroscopic descriptions that did not include the particle level and its interactions, to careful attention to the stochastic interactions at the submicro-level, culminating with an increased attention to submicro-level interactions and connecting these to the macro-level of the observed phenomena.

Discussion

This discussion addresses the concepts learned, interactions with the sound-based model and the process of learning, and implications for educational settings. It is important to note two limitations in the design of this

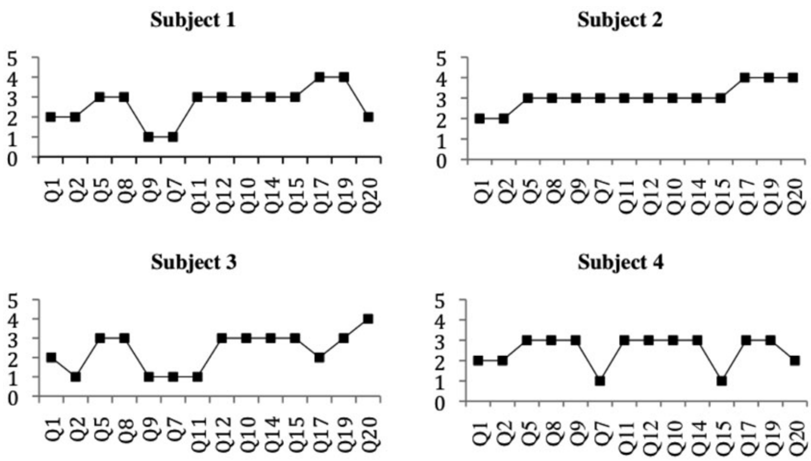

Fig 4 Progression of explanations in terms of levels. *X*-axis is the question number in the activity. *Y*-axis is the level of the answer as described in the text: no answer (1), focusing on the macro-level (2), the submicro-level (3), or relating the two (4).

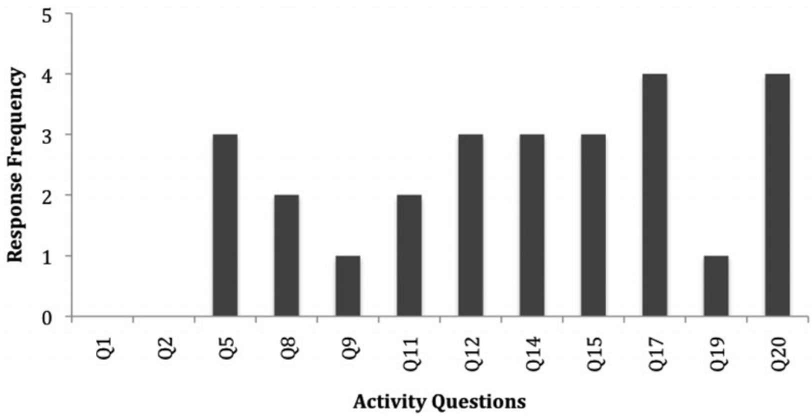

Fig 5 Number of subjects that described interactions among objects at the micro-level.

study. One is the small sample size. A second is that testing was conducted with adults rather than middle school children, for whom this environment is designed. Future research will enlarge the sample to include younger participants.

Interactions with the sound-based model

The participants perceived most, but not all, representations as their referents. They easily mapped each separate representation and its referent. However, once representations were combined, we found a limit to what could be integrated. When one representation had a single pitch and the other a changing pitch, they could be combined and reasoned with. However, when the two representations had several pitches (wall hits and changing speed), this proved to be too much to process; less learning was evidenced during the activity and no residual understanding was detected at the end. This failure of the design is reflected in the participants' not learning how a particle's hitting the wall is distinct from particles' collisions in terms of speed and energy and in their comments regarding information overload. Further design and additional training and intervention with the environment may prove more beneficial to learning.

Regarding construction of a conceptual understanding, several impressive results were seen. Starting with the very first listening to the model, participants generated richly detailed descriptions of a single gas particle's motion. These descriptions made use of both the representations and additional assumptions, such as the particles' straight-line motion. The representations highlighted the randomness of the particles' motion and interactions and accordingly this idea was incorporated into several of the provided explanations.

Most remarkable was the perception of an 'average speed' by some of the participants. A difficult invariant to grasp – the constancy of average speed in face of its rapidly changing value, expressing the basic concept of *dynamic equilibrium* – was gleaned from listening to the model.

Learning of scientific concepts

Through interaction with the sound-based model, two scientific concepts were learned: understanding the random behaviour of gas particles and incorporating a particulate view in making sense of a physical system. In such a short activity, we find these learning gains significant in terms of their centrality to understanding both the science content (Johnstone 1993) and systems (Bar-Yam 1997). In chemistry, relating molecular descriptions with those of physical phenomena and understandings gas particles' random behaviours are difficult for learners (Novick & Nussbaum 1981; Nussbaum 1985; Westbrook & Marek 1991). In understanding a complex system, its stochastic nature and 'thinking in levels' are both challenging and central to reasoning (Resnick 1994; Penner 2000; Jacobson 2001). As these two ideas proved significant and consistent in the learners' articulations during the activity, we see a clear relationship between interactions within the activity and this learning.

Process of learning the science content

The learning experience in this study was designed as a progression of activities, each geared to particular learning goals. An analysis of the participants' articulations in terms of the scientific principles shows that most of the learning goals were met. Two ideas were expressed across several activities – the particulate nature of the matter and the randomness of particles' behaviours – and these were the very same concepts that were learned and sustained. Thus, while an idea may be learned *in situ*, its re-use in several contexts is related to the stability of its understanding. Ideas that were understood temporarily in a particular section, but were not revisited or reframed, were not maintained.

Alternative conceptions regarding the particles' behaviours compete with scientific ideas. The alternative ideas identified in this study are provided inconsistently, correspond with those reported in the literature and relate to energy transformations, where energy is removed or added through collisions. Similar ideas have been found in previous research by one of the authors and colleagues with sighted participants (Levy *et al*. 2006) and in reports on undergraduate students' views that an increased rate of collisions causes particles to become faster (Loverude *et al*. 2002). Most common was the idea that collisions among objects consume energy, which makes sense from everyday experience of inelastic collisions. In future design, this concept will be addressed and explored.

The activity started out with a physical-world experience, inflating and palpating a bicycle tire. The reason for this choice is the centrality of connecting and referring to real phenomena in model-based learning (Schecker 2003; Levy & Wilensky 2009a). When returning to the phenomenon through exploring the model, we have seen detailed and careful reasoning about both particles and the system-wide phenomena. This shows how prior knowledge is elicited through the physical experience and later serves to frame and relate to new information, incorporating it into a multi-faceted and deeper understanding.

One of the interesting findings is that principles relating to the particles' direction of motion, which *was not represented in the model*, were expressed during the activity. It would seem that these *spatially* based principles were harnessed from the participants' prior knowledge and incorporated into an enriched mental model of the particles in motion. Using the wall representation, the participants went beyond it and created a full path of motion in the space of the container. One may conclude that not all information needs to be included in the computer model. Future research should address this balance between representing enough critical information to support creating a detailed mental model and yet not overloading the cognitive system. We propose that this research be content-specific, as information that does not necessitate cues is probably related to prior knowledge.

The computer model's representations focused on properties and events relating to one particle. In terms of systems reasoning, the results show that the participants were quite capable of making a connection between these local stochastic interactions of a single particle with the macro-level phenomenon. This was a culmination of a progression that began with experiencing the physical system and then carefully exploring its submicro-level rules and behaviours. When the macro-level was later introduced, not only did expressions of local interactions not diminish but they also increased. Macro-level properties and dynamics were described as emerging out of the interactions at the submicro-level, systems reasoning at its best.

Implications for educational settings

The results of this investigation have shown gains both in learning the science content and in understanding systems. The long-term practical benefits of this research are likely to have an impact on STEM education for students who are blind, as equal access to low-cost learning environments that are equivalent to those used by sighted users would support their inclusion in the middle school to undergraduate academic curriculum. While the current investigation concerns a particular topic in chemistry, such a representation can be used for a wide range of STEM topics: physics (e.g. free-falling bodies, pendulum oscillations), biology (e.g. circulatory system, ecological systems), chemistry (e.g. reactions), engineering (e.g. gear mechanisms), and mathematics (e.g. graphs). As most students who are blind are integrated into the regular educational system, it would be necessary to support the science teachers with ways of incorporating the L2C tools into the class curriculum and guiding teachers in the use of such environments.

We have garnered knowledge from problems that arose in this study and from our participants' suggestions. Regarding sonification, we have learned about the needs of limiting the amount of information that can be integrated in a single hearing and of distinguishing related sounds of a single variable more clearly. In terms of learning supports, there is a need to revisit some of the more problematic ideas identified in the study through a variety of contexts, appropriate feedback, and explicit instruction. Shifting control to the user is essential to making this a truly exploratory environment. The role of sonification shows a learning advantage in more interactive settings (Pauletto & Hunt 2009). In addition, this environment uses both visual and sound-based representations, thus providing an environment geared for integrating students who are both sighted and blind in collaborative learning. Future design and research will support such interactions.

Note

[1]L2C denotes Listening to Complexity, the name of the reported research project.

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