Computers & Education 127 (2018) 141–153

Contents lists available at ScienceDirect

Computers & Education

journal homepage: www.elsevier.com/locate/compedu

Listen to the models: Sonified learning models for people who are blind

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ARTICLE INFO

Keywords:
Blind
Computer-based learning
Sonification
Learning
Science education

ABSTRACT

Students who are blind need access to learning materials. This study looks at the learning of science by people who are blind using a curriculum-based textbook compared to their learning using an identical curriculum integrated with the Listening-to-Complexity (L2C), an agent-based model created on NetLogo. The L2C system employs sonified feedback that provides auditory streams synchronically. This study examines acquisition of scientific conceptual knowledge and systems reasoning for the Kinetic Molecular Theory (KMT) of gas and Gas Laws in chemistry. Twenty persons who are blind participated in this research; they were divided into two experimental groups: those using an accessible curriculum-based textbook and those using the same curriculum integrated with L2C agent-based models. Results showed that all research participants gained scientific knowledge; statistically significant differences were found for both experimental research groups between pre-and posttest. Those who learned through the L2C models performed with higher accuracy in the posttest; furthermore, learning using the NetLogo L2C models predicted their success at the posttest. A comparison of learning task accuracy between the two experimental groups showed that the participants who studied using the NetLogo L2C models performed with statistically significant differences in the five learning activities with integrated L2C models, but no differences were found for the learning activities without integrated L2C models. These research results are likely to have a beneficial impact on integrating sonified models in science education as a compensatory aid, allowing hands-on learning experience for students who are blind. Integrating sonified models will support their inclusion in the K–12 academic curriculum on an equal basis.

1. Introduction

Students who are blind compensate for visual loss using perceptual information obtained through the haptic, auditory, and olfactory senses (Bishop, 2004). Despite the "developmental lag" that people who are blind experience (Warren, 1994), they process most cognitive information much as do people with sight. Differences between students who are blind or sighted occur in the modes of information collection, but in the cognitive structures and operations processes, the dissimilarities fade (Hollins, 2000). For the past 80 years, K–12 students who are blind have been integrated in general education schools with their sighted peers and are required to complete the same curriculum and examinations. One of the main objectives of integrating students who are blind is to

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https://doi.org/10.1016/j.compedu.2018.08.020
Received 25 January 2018; Received in revised form 7 June 2018; Accepted 21 August 2018
Available online 23 August 2018
0360-1315/

provide them the same opportunities and educational experiences as those provided for sighted children (Mani, 1998). The science, technology, engineering, and mathematics (STEM) curricula rely heavily on visual imagery in tables, plots, graphs, diagrams, charts, and models and in exploration in science laboratories (Beck-Winchatz & Riccobono, 2008). Without vision, students who are blind are left to gather information through a compensatory channel such as the auditory or tactile sense, placing them at an immediate disadvantage. Equal access to STEM learning materials can enable the majority of students who are blind to accomplish STEM-related tasks on par with their peers with sight (Klingenberg, Fosse, & Augestad, 2012). To date, few guides have been written on how to teach science to students who are blind (Kumar, Ramasamy, & Stefanich, 2001), and, unfortunately, research into the application of these techniques and their impact on learning is sparse. To integrate students who are blind in science classrooms and laboratories, researchers have suggested reforms such as providing accessible learning materials in braille, audio, large print; tactile diagrams and graphs; specific instructions; and using real objects for hands-on learning experiences (American Association for the Advancement of Science (AAAS), 1991; De Oliveira, Nascimento, & Bianconi, 2017; Dick & Kubiak, 1997; Toenders, de Putter-Smits, Sanders, & den Brok, 2017a). Moreover, teachers devote a considerable amount of time developing accessible learning materials and teaching one-on-one during regular classroom activity (Toenders, de Putter-Smits, Sanders, & den Brok, 2017b).

1.1. Assistive technology for people who are blind

Assistive technology in education for students who are blind plays a valuable role in enabling them to be independent and in enhancing their literacy, learning, and social skills (Taylor, 2016). Furthermore, assistive technologies provide an equal opportunity to participate in learning environments with peers with sight (Douglas, 2001). These technologies are based on tactile resources, large print, or audio. Auditory tools compensating for lack of visual information include screen readers and sonification, the presentation of information using nonspeech sound (Kramer, 1994). Although screen readers provide quality access to text materials, students who are blind face greater obstacles in using the technology. STEM materials are especially challenging because of their unique symbols, characters, and nonlinear writing style (Nees & Berry, 2013; Power & Jürgensen, 2010). Assistive devices and software have also been developed to support STEM education for students who are blind, for example, Talking Tactile Tablets (Landau, Russell, Erin, & Gourgey, 2003), based on audio and 2D tactile images for learning mathematics and science diagrams. In their overview research, Scalise et al. (2018), in addition to implementing the universal design learning (UDL) methodology (CAST, 2011), accommodated future development of digital interactive STEM simulations to ensure accessibility for STEM assessments. Jones et al. (2014) developed a haptic simulation that allows elementary and secondary students who are blind to learn about particle motion, temperature, and pressure; students can feel particle movement as it varies with different temperature and pressure settings. Line Graphs technology is based on auditory and haptic feedback and is geared to learning mathematics (Ramloll, Brewster, & Burton, 2000); the force-feedback mouse for physics study is another tool (Farrell, Baldyga, & Erlandson, 2001, chap. 21, pp. 308–309). One of the first sonification system developments for people who are blind was the vOICe project (Meijer, 1992). Many researchers have followed up on Meijer's work. Amedi, Raz, Pianka, Malach, and Zohary (2003) studied various perception topics, including memory. Binev et al. (2018) developed the NavMol, which auditorily describes the molecular structures and enables students who are blind to use a molecular editor for metabolic reactions. Leuders (2016), in her research on mathematics learning by children who are blind, concluded that auditory perception is the most suitable sensory channel for the processing of temporal information.

1.2. Understanding complex systems

Complex systems are made up of many elements that interact among themselves, self-organizing in coherent global patterns (Bar-Yam, 1997). In the past three decades, the field of complex systems has developed enormously, contributing to our understanding of a wide range of systemic phenomena (Barabasi & Bonabeau, 2003). It has provided a framework for representing and comprehending the structure and dynamics of systems, focusing on generating global patterns from local behaviors and interactions. The framework's wide applicability presents a powerful paradigm for interpreting systems. Goldstone and Wilensky (2008) argue that learning about complex systems cases is pedagogically valuable because it helps students in (a) organizing science phenomena according to complex systems principles, bestowing on students the benefits of new, rich perspectives; (b) bridging explanations on two levels (explaining large-scale, macrolevel phenomena in terms of local, microlevel events); (c) grounding for formalisms; and (d) cross-fertilizing between sciences as a result of the use of common principles across cases. Complex systems challenge our understanding, as several biases sway people's reasoning: confusion among levels (Wilensky & Resnick, 1999), a focus on the system's structure at the expense of function and mechanism (Hmelo-Silver & Pfeffer, 2004), and a tendency to view causal relations as a consecutive chain of causes and effects rather than as parallel concurrent interactions (Chi, 2005). These difficulties point to the importance of educational support in making sense of systems. Several innovative learning environments have been designed to help people overcome these biases and understand complex systems; these include constructing and exploring computer models (Levy & Wilensky, 2009a, 2009b; Wilensky & Resnick, 1999) and participating in role-playing simulations (Klopfer, Yoon, & Perry, 2005). Agent-based modeling is a computational modeling paradigm that simulates complex dynamic systems by simulating each of their many autonomous and interacting elements. NetLogo (Wilensky, 1997) enables construction of models of complex systems by programming and running the rules of numerous entities. The NetLogo modeling platform was used to create a computer model (Levy & Wilensky, 2004) based on previous research on learning about complex systems using models with students with sight (Levy & Wilensky, 2009a, 2009b).

In chemistry education, one of the central frameworks presented by Johnstone (1993) is that a well-developed understanding of a chemical system needs to relate three forms of description that map nicely onto a complexity perspective: the submicroscopic level, the macroscopic level, and representations. Learning about the particulate nature of matter is one of the main learning topics in chemistry in the seventh grade. In the last two decades, studies have demonstrated students' difficulties in consistently understanding and internalizing the particulate nature of matter model; a large percentage continue to harbor misconceptions in this topic (Chiu, 2007; Linn & Eylon, 2011; Novick & Nussbaum, 1978). Previous research describes several common difficulties in understanding chemical systems, particularly with respect to the topic of gases (Ben-Zvi, Eylon, & Silberstein, 1986); most high school students do not base their explanations upon a particulate view of matter and assign macrobehaviors to gas particles such as expansion and heating (Nussbaum, 1985); many view gas particles as being pushed down by atmospheric pressure and keeping away from heat (Lin & Cheng, 2000); some view gas as weightless (Mas & Perez, 1987); students also have difficulties incorporating the idea of random particle motion in a gas or liquid (Novick & Nussbaum, 1978). Of the 300 students Westbrook and Marek (1991) examined for understanding of the diffusion concept, none across three grade levels exhibited complete mastery. Samon and Levy (2011) studied junior high school students' learning of chemical systems with an agent-based versus a textbook approach. Their results showed that students scored higher after learning with agent-based models, particularly when micro- and macrolevel behaviors were distinct.

1.3. The current study

As noted, most STEM curriculum materials are not accessible for students who are blind. In this research, we aim: (a) to improve our understanding of perception of sound streams and their transformation into conceptual thought through interactions with Listening-to-Complexity (L2C) systems, (b) to examine the learning processes based on the L2C activities, and (c) to explore the STEM learning of learners who are blind and to compare the learning between those who learned through a curriculum-based textbook to that of those who learned through an identical curriculum with added interactions based on the NetLogo L2C activities. In the current research, we followed the AAAS (1991) and others (Kumar et al., 2001) who suggested reforms in developing curricula for students who are blind. The curriculum we used for this research is Chapter 1 of the Connected Chemistry curriculum (CC1) for learning Kinetic Molecular Theory (KMT) of gas in chemistry (Levy, Novak, & Wilensky, 2006), which was developed for sighted students. To make CC1 accessible to students who are blind, it has been altered using UDL methodology (CAST, 2011). For example, we described images and tables; included specific instructions; created tactile diagrams, graphs, and images; and produced the material in braille and audio file. In accordance with the recommendation of Supalo, Humphrey, Mallouk, Wohlers, and Carlsen (2016) to use technology to increase students' hands-on learning experiences, we included the L2C computer model inquiry activities that allow participants to explore computer models of complex systems and to study systems reasoning through a complexity perspective. These activities are based on the NetLogo system; the L2C models are based on the transmittal of visual information of dynamic and complex systems, providing perceptual compensation by harnessing auditory feedback. Use of sonification output reaps the benefits of auditory properties: (a) it transmits information that changes both in space and time, like the visual modality; (b) the auditory modality easily interfaces with large bandwidths at fine frequency-discrimination and intensity-discrimination thresholds (Capelle, Trullemans, Arno, & Veraart, 1998); (c) the auditory modality is able to deal with rapidly changing sound patterns (Hirsh, 1988). This is the first study in which participants have been able to access dynamic rather than static information in exploratory science learning that is happening in real time; each time they run the model with the same variables a new scenario is represented. The study examines four research questions:

1. What level of scientific knowledge had the participants in each experimental group achieved as shown in the pretest?
2. How did both experimental groups perform in their learning tasks with and without L2C activities?
3. What level of scientific knowledge did the participants in each experimental group achieve as demonstrated in the comparison between the pretest and posttest results?
4. How does the learner model compare in both experimental groups in terms of accuracy of responses in the pretest, posttest, and learning activities?

2. Method

2.1. Participants

The study included 20 participants who were selected based on three criteria: total blindness, no additional disabilities, and no previous study of the KMT of gas. These two criteria were verified by participants' self-reports and by representatives of organizations for the blind, who aided us in recruiting them. The participants were randomly assigned to two experimental groups; each included 10 participants. The first experimental group (Group 1) studied through the CC1-based textbook. They were aged 19–28, $M = 24$, $SD = 2.68$; nine were male; nine were congenitally blind; and three had residual vision (light perception). Eight were undergraduate students, and two worked in a factory. The second experimental group (Group 2) studied through the CC1, with embedded NetLogo L2C interactions. They were aged 17–33, $M = 23$, $SD = 5.38$; four were male; eight were congenitally blind; and four had residual vision (light perception). Two were high school students, six were undergraduate students, and two worked in education. None of the participants who had residual vision used it for reading or writing. All participants had studied science in school, but not at college or university. Both groups were at an equal level of knowledge regarding Kinetic Molecular Theory (KMT) of gas, since none of them had studied it before. All participants knew how to operate computers for daily use. Most research participants ($n = 19$) read and wrote braille, but during the research sessions all participants preferred to use the auditory file and tactile images (pre- and posttest questionnaires and CC1). Participants were recruited with the help of organizations for the blind and through snowball sampling. The review board of the University Ethics Committee approved the research.

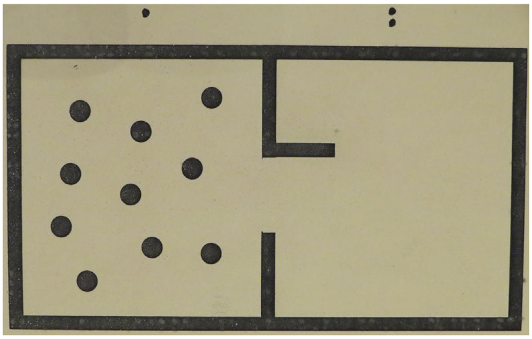

Fig. 1. Tactile image from the pre- and posttest questionnaire.

2.2. Instrumentation

The research included four data collection tools, described below.

2.2.1. Background questionnaire

This questionnaire included 17 questions on personal information, science education, and computer technology use.

2.2.2. Pre- and posttest questionnaires

We administered identical pre- and posttest questionnaires, including four sets with questions in different order; hence each participant got two sets. The questionnaires assessed understanding of gas laws and KMT, included multiple-choice (22) and open-ended (three) questions (Appendix A). The questionnaire consists of questions that are based on the seven CC1 activities: modeling a basketball, particles in a container, the KMT of gas, pressure, changing pressure, diffusion, and atmospheric pressure and gravitational force. As the questionnaire progressed, the questions increased from simple to complex.

Most questions were a subset of those that had been previously used to assess sighted students' learning of similar topics (Levy & Wilensky, 2009b). Issues of validity were addressed through a systematic analysis and mapping between CC1 and the pre- and posttest questionnaire, employing items previously used in other studies and several rounds of review by two research teams. The questionnaire had been developed for sighted students; to make it accessible to students who are blind we made some changes using UDL methodology (CAST, 2011). These questionnaires were available to the participants as a text-to-speech file and in braille with tactile images (Fig. 1). All tactile images were printed in a Swell-Form Graphics Machine (a fuser) manufactured by Zychem by using a standard print on Swell-Touch paper. The heat from the machine reacts with the black ink and causes it to “swell” creating the tactile shapes. The size of the tactile shapes was designed according to guidelines and standards for tactile graphics for people who are blind in North America (Miller et al., 2012). The size of the tactile images was between 5 and 8 cm, a size that can be explored with two hands at the same time.

2.2.3. Learning materials

The learning materials were based on CC1, a standard learning program for learning KMT of gas in chemistry designed by Levy et al. (2006). This curriculum consists of a sequence of seven activities: (a) modeling a bicycle tire: after generating a theoretical model of pumping up a bicycle tire or a ball, the system presents the computer model of gas particles in a container, leading to the KMT of gas assumptions that are subsequently explored; (b) experimenting with particles: the user is able to explore, design, and conduct the model's behavior by changing the particles' properties and adding particles to the model—these changes cause particle-to-particle and particle-to-wall collisions and affect particle speed; (c) the KMT of gas; (d) pressure: the user investigates and learns that pressure is caused by particles hitting a surface; (e) changing pressure: the user explores phenomena that impact pressure, such as: the effects of quantity of particles, the frequency at which individual particles hit the wall, the effect of the container volume; the concept of energy is explored further by relating changes of the gas temperature and the speed of the particles, delays between heating the container and heating the gas are observed and explained, and the qualitative and quantitative relationships between temperature and pressure are investigated; (f) diffusion: understanding diffusion phenomena, such as what an odor is, transmitting messages by odor, diffusion of a new gas, diffusion of pheromones in the air, the influence of the model's volume on diffusion speed, the influence of number of particles on diffusion speed, and the influence of temperature on diffusion speed; and (g) atmospheric pressure and gravitational force: users explore how pressure varies with altitude and experiment with gravitational force and atmospheric pressure. This original curriculum was translated into Hebrew and evaluated by a research team led by one of the researchers who designed the original curriculum (Samon & Levy, 2011). The CC1 (English and Hebrew versions) was used in different schools as a learning material to study KMT of gas. For the current research, we used the CC1 Hebrew version (Samon & Levy, 2011) and made it accessible for learners who are blind using the UDL methodology (CAST, 2011). These changes included describing images and tables, integrating specific instructions, creating tactile images (e.g., diagrams, charts), and editing and saving in special formatting (plain text). Participants were able to read (braille) or listen (text-to-speech) to CC1 and to explore the tactile images accordingly. Two curricula were created from this adaptive CC1 Hebrew version, each of which stands by itself as learning material.

Table 1
The two curriculums.

	CC1-based textbook			CC1 with embedded sonified models			
	Open-ended	Multiple-choice	Sum	Open-ended	Multiple-choice	Sum	NetLogo L2C
Modeling a bicycle tire	7	4	11	7	4	11	0
Experimenting with particles	5	29	34	5	29	34	10
The KMT of gas	1	1	2	1	1	2	0
Pressure	2	3	5	2	3	5	1
Changing pressure	18	65	83	22	65	87	11
Diffusion	15	38	53	14	39	53	5
Atmospheric pressure and gravitational force	8	3	11	8	3	11	2
Sum	56	143	199	59	144	203	29

2.2.3.1. CC1-based textbook. The CC1-based textbook includes only the learning material without the NetLogo L2C interactions or questions that are related to these interactions. This curriculum was examined and approved by three science teachers as a curriculum that stands alone and is suitable to teach KMT of gas. This curriculum included 199 questions: 56 open-ended questions and 143 multiple-choice questions (Table 1).

2.2.3.2. CC1 embedded sonified models. This curriculum was identical to the CC1-based textbook described above, except that here NetLogo L2C models were integrated into the curriculum for five of the seven learning activities. The original sonified NetLogo model was developed by Levy and Wilensky (2004). This model includes an observation of the behavior of one particle in a container. The user is able to modify the setup scenario (initial number of particles; number of particles to add during the model; initial gas temperature; and a container with closed or open wall, or without wall); and the total speed of the model (Fig. 2a). For the current research, we developed a L2C model based on the original sonified NetLogo model and usability study results. It conveyed auditory information regarding the behavior of gas particles in a container; each event (particles colliding with wall, particle collisions, and adding particles to the container) or systemwide phenomena (such as velocity, temperature, and pressure) in the model had a unique sound. These sounds were related in their semantics to the referent; for example, for sonifying particle collisions we chose billiard ball collisions: two billiard balls—same material—collide with one another. Through the L2C interactions the user was gradually exposed to two to five sounds. Stifelman (1994) has demonstrated that this gradual exposure aids in building stream segregation, thus enhancing audio perception and enabling participants to increase the number of perceived channels beyond three. This sonified feedback can be activated by on/off buttons, shown at the bottom of Fig. 2. In each activation of a new setup, the particle behaves

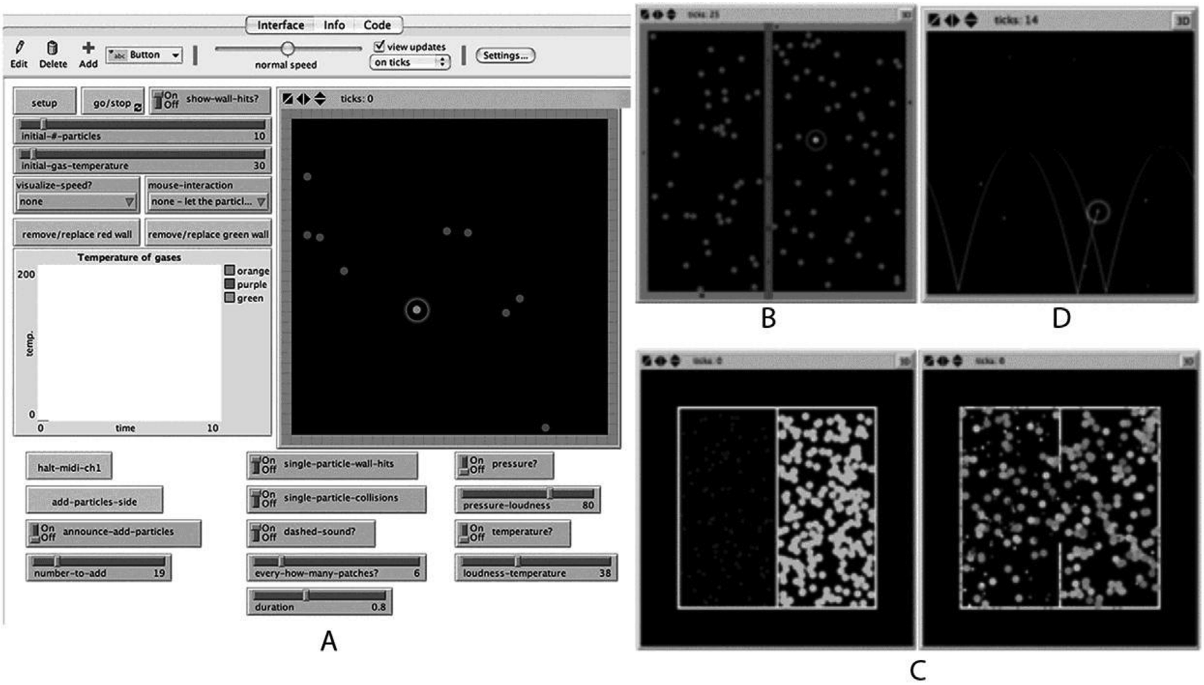

Fig. 2. L2C sonified models of gas particles in a container: (a) Experimenting with particles; (b) Changing pressure; (c) Diffusion (closed and open wall); and (d) Atmospheric pressure and gravitational force.

accordingly; as a result, the model makes a different “melody” respective to each new setup.

The learning materials included an operational description of each L2C activity. For example, in the third L2C activity the participants learned about particle collisions, and the description of the activity suggested activation of two sonified buttons: “single-particle-wall-hits” and “single-particle-collisions.” Using this sonified feedback the participants could detect individual gas particles colliding through the sound of two billiard balls colliding and could perceive particles hitting the wall of the container through the sound of a bat hitting a baseball. For learning about systemwide phenomena such as velocity, L2C provides spatial audio graph sounds. The video at the link below provides at the beginning visual and sonified feedback and later it provides only the sonified feedback of the L2C model, portraying the third and fourth L2C activities described below. It includes two sonified events: particles colliding with wall and particle collisions; at the end two more events gradually appear, one audio graph representing velocity and an event representing addition of particles to the container (https://youtu.be/BQpM-oM7hI8).

This curriculum included 203 questions: 59 open-ended questions, 144 multiple-choice questions, and 29 NetLogo L2C model interactions (Table 1); six focused on the participants' familiarization with the sonified feedback. These 29 NetLogo L2C model interactions were integrated into five of the seven CC1 learning activities. The five activities included: experimenting with particles (Fig. 2a), pressure, changing pressure (Fig. 2b), diffusion (Fig. 2c), and atmospheric pressure and gravitational force (Fig. 2d). Instructions on the use of each L2C interaction were given in the curriculum. These instructions included information on what participants could change or add to the model, or what buttons they could ask the researcher to activate or stop. For example, the participants in the first L2C activity became familiar with adding particles to the container, in the second activity, they were introduced to the particle colliding with walls, and in the third activity they focused on particle collisions. For example, the third L2C activity included the following instructions: *To add the rule "particle collisions," ask the teacher (the researcher) to do the following:*

1. *Open the model in your computer.*
2. *Press the SETUP button.*
3. *Select the initial number of particles (between five and 10).*
4. *Activate the SINGLE-PARTICLE-WALL-HITS*
5. *Run the model by pressing the STOP/GO button and listen to the sound.*
6. *Activate the SINGLE-PARTICLE-COLLISIONS to add the sound of particle collisions.*
7. *Listen to the two sounds: particles colliding with wall and particle collisions.*

Unfortunately, in this version of L2C the participants were unable to operate the models independently, they gave instructions to the researcher, who operated them accordingly. We hope that the next version will allow the user to operate the L2C independently. The researcher did not give feedback on performance or explanations at any stage during the L2C activities or in any other research session.

2.2.4. Screen recording

To record Group 2 participants' interactions with L2C we used LogSquare, a screen recording software that simultaneously records the user's entire experience, audio and video and computer-related activities, such as mouse actions and keyboard entries made during a test session.

2.3. Data analysis

All participants in both research groups answered all questions; there was no missing data. To evaluate a participant's performance, we applied two coding schemes that had been developed in previous research and were used to analyze participants' answers on the pre- and posttest questionnaires and in the learning intervention (Levy & Wilensky, 2009b; Samon & Levy, 2011). These two coding schemes included all answers to the multiple-choice as well as the open-ended questions. Multiple-choice questions were coded as correct or incorrect, and open-ended questions were coded by two researchers for the relevant correct scientific principles they included based on the coding schemes. Each open-ended question had an answer in one of the coding schemes that described the structure of the correct explanation based on scientific content and systems reasoning (descriptive, microlevel, and macrolevel) (Jacobson, 2001; Wilensky & Resnick, 1999). For the duration of the activity, the data for both research groups was collected by the researchers; the duration of L2C activities was also collected by LogSquare screen recording software. For the pre- and posttest, descriptive statistics were compared, and progressions of frequencies were computed and related to the activity.

To assess the validity of the data, two researchers individually analyzed all the participants' performances. Later, the two researchers' analyses were compared, and 83% of their evaluations were identical; for the other 17%, three researchers discussed the participants' performances and arrived at agreement about them.

The quantitative analysis made use of statistical software (Excel and SPSS). Qualitative analyses were focused on participants' behaviors and learning process. Repeated measure General Linear Model (GLM), ANOVA, linear regression, and independent sample *t*-tests were carried out in order to detect significant differences.

2.4. Procedure

The research consisted of 10 sessions that were distributed over five to eight weeks. The learning sessions lasted not more than 60 min each. In the first session, all participants or their legal guardians signed a consent form and participants completed background and pretest questionnaires. The duration of the pretest was approximately the same in both groups (44 min). Next they studied CC1; Group 1 used only the CC1-based textbook and Group 2 used the identical curriculum with the L2C sonified models integrated into it. Group 1 spent an average time learning CC1 of 05:41:00 and Group 2 spent an average time learning CC1 of 06:16:00, which included the average 00:49:00 duration of L2C activities (an average of 00:01:40 for each L2C task; the L2C activities focused on diffusion and atmospheric pressure and gravitational force required an average of 2 min). There was no extra session to familiarize participants with the L2C system; they learned it and became familiar with the sonified feedback as part of the L2C activities (e.g., activities 1, 2, 3, 4, and 11).

The last session included the posttest questionnaire. The posttest lasted approximately the same amount of time in both groups (35 min). Throughout the research, all the participants in both research groups were observed individually at their home by a researcher. All participants preferred to listen to the auditory file and to use tactile images, then to reading the curriculum in braille. After listening to the question (multiple-choice or open-ended) in the pretest, posttest, and during the learning process, all the participants in both research groups responded orally to the researcher without receiving feedback on performance or explanations at any stage. There was a folder for each participant with all the questionnaires (pretest, posttest, and learning process), in which the researcher recorded the participants' responses in their own words.

3. Results

Research Question 1: What level of scientific knowledge had the participants in each experimental group achieved in the pretest?

In order to examine the participants' scientific knowledge level for KMT of gas before starting the CC1 learning stage, an independent sample *t*-test (while combining multiple-choice and open-ended questions) was conducted. This test was found to be statistically nonsignificant (t (18) = 2.00, p = .060). These results indicate that participants in Group 1, which studied using a CC1-based textbook (M = 46, SD = 6.98), achieved a slightly lower score than did participants in Group 2, which studied using an identical curriculum integrated with L2C interactions (M = 54, SD = 10.12). Nonsignificant differences were found between the two groups in both types of questions: multiple choice (t(18) = 1.75, p = .098) and open-ended (t(18) = 0.02, p = .102) (Table 2).

Research Question 2: How did both experimental groups perform in their learning tasks with and without L2C activities?

To examine the learning process a 5 × 2 repeated measure ANOVA was conducted on accuracy of responses. The factors for analysis of accuracy of responses were the five activities from CC1, which integrated L2C interactions: experimenting with particles, pressure, changing pressure, diffusion, and atmospheric pressure and gravitational force; and the two experimental research groups. As to differences between the two experimental groups, the analysis showed that participants in Group 2, who studied using a CC1-based textbook with integrated L2C interactions (M = 79), had overall a statistically significant higher number of correct responses in the learning activities as compared with participants in Group 1, who studied using the CC1-based textbook only (M = 65), (F(2.274, 40.923) = 4.34, p = .016, η^2 = 0.19). A post hoc Tukey test showed that between the two research groups the accuracy of response for pressure and atmospheric pressure and gravitational force activities differed significantly at $p < .0000$. This analysis has shown that for the comparison of pressure activity the accuracy of Group 2 was statistically significantly higher than for Group 1 (80% vs. 51%, respectively); accuracy also differed statistically significantly for the atmospheric pressure and gravitational force activity between the two experimental groups (60% vs. 26%, respectively). Therefore, we can conclude that Group 2, which learned through a CC1 with L2C interactions, achieved statistically significant more scientific knowledge in activities with integrated L2C interactions.

A repeated measure ANOVA was conducted for the two learning activities from the CC1 for which the L2C interactions were not integrated. The results showed nonsignificant differences between the two research groups for these interactions.

Table 3 presents both experimental groups' mean of scientific knowledge performance in the learning activities. Group 1, which studied using only the CC1-based textbook, displayed a lower accuracy of responses compared to the participants in Group 2, whose learning experience included interaction with the NetLogo L2C models (65% versus 79%, respectively). This gap persisted in multiple-choice questions (76% versus 84%, respectively) and a larger gap was found in the comparison of the open-ended questions (35% versus 69%, respectively). Accuracy of responses was higher in multiple-choice questions than in the open-ended questions for both groups.

Research Question 3: What level of scientific knowledge did the participants in each experimental group achieve as demonstrated in the comparison between the pretest and posttest results?

To examine the overall group effect we conducted a 2 × 2 repeated measure ANOVA accuracy of responses. The factors for

Table 2
Comparing participants' accuracy of responses in pretest.

	Group 1		Group 2	
	M	*SD*	*M*	*SD*
Total	46%	6.9	54%	10.1
Multiple choice	50%	7.9	59%	12.6
Open-ended	23%	3.7	29%	9.6
Diffusion	49%	9.2	57%	13.4
Pressure	14%	7.7	16%	16.5
Atmospheric pressure and gravitational force	7%	8.4	14%	11.5

Table 3
Accuracy of responses for both experimental groups in the learning activities.

Learning activities	Group 1			Group 2			t
	Open- ended	Multiple choice	Mean	Open- ended	Multiple choice	Mean	
Modeling a bicycle tire	36%	73%	52%	49%	85%	65%	
[a]Experimenting with particles	17%	71%	63%	62%	81%	78%	
The KMT of gas	30%	80%	55%	50%	80%	65%	
[a]Pressure	63%	40%	51%	80%	80%	80%	0.000
[a]Changing pressure	41%	77%	70%	75%	84%	81%	
[a]Diffusion	35%	84%	72%	68%	87%	82%	
[a]Atmospheric pressure and gravitational force	20%	40%	26%	56%	70%	60%	0.000
Mean	35%	76%	65%	69%	84%	79%	0.016

[a] Activity integrating NetLogo L2C interactions.

analysis of accuracy of responses were the participants' responses at pretest and posttest as to differences between the two experimental groups. The analysis showed ($F(1, 18) = 102.48$, $p = .000$) a statistically significant difference for both experimental groups; all research participants gained scientific knowledge between the two tests; the pretest mean (50%) was lower compared to posttest results (72%).

Furthermore, we compared both groups' accuracy of responses in the pre- and posttest to explore the scientific knowledge that each group had acquired as a result of its unique learning process. A paired sample *t*-test showed that the total accuracy of responses in Group 1 between the pretest ($M = 46$, $SD = 6.98$) and posttest ($M = 66$, $SD = 6.38$) questionnaires demonstrated a significant difference in performance ($t(9) = -5.96$, $p = .000$). A statistically significant difference in performance was also found for Group 2 in the total accuracy of responses for the pretest ($M = 54$, $SD = 10.12$) and posttest ($M = 77$, $SD = 9.20$) questionnaires ($t(9) = -6.14$, $p = .000$). Both experimental groups gained scientific knowledge during the period between the pretest and posttest, although each experienced a different intervention during this period.

To examine the participants' scientific knowledge differences at the posttest, we compared accuracy of responses in the posttest questionnaire for the two experimental groups. An independent sample *t*-test was conducted. Results indicate that participants in Group 1 ($M = 66$, $SD = 6.38$) achieved a lower score than did participants in Group 2 ($M = 77$, $SD = 9.20$) and demonstrated a statistically significant difference in performance ($t(18) = 3.26$, $p = .004$). Differences between the two groups in both types of questions were statistically significant: in multiple-choice questions ($t(18) = 2.93$, $p = .009$) and open-ended questions ($t(18) = 3.83$, $p = .003$) (Table 4).

Research Question 4: How does the learner model compare in both experimental groups in terms of accuracy of responses in the pretest, posttest, and learning activities?

A simple linear regression was calculated to predict posttest accuracy based on pretest and learning process accuracy for both research groups. The pretest and learning process did not succeed in predicting the posttest accuracy for Group 1 ($R^2 = 0.353$, $p = .218$); two beta values were not significant: pretest $\beta = 0.337$, $p = .324$, learning process $\beta = 0.596$, $p = .103$. For Group 2, only the learning process succeeded in predicting the posttest accuracy ($R^2 = 0.526$, $p = .074$); one beta value was significant: pretest $\beta = 0.156$, $p = .571$; learning process $\beta = 0.687$, $p = .05$. As shown above, studying using the NetLogo L2C models predicted participant success in the posttest. Comparison of average accuracy of responses in the pretest and learning activities (Fig. 3) shows half of participants scoring 31 to 42 points higher on the learning activities evaluation compared to their score on the pretest, and 70% of the participants retained this higher score in the posttest. In the other experimental group, which studied using only the CC1-based textbook (Fig. 3), only 10% scored over 30 points higher on the learning activities evaluation compared to their score on the pretest. Most (80%) scored 11 to 26 points higher and 80% retained this score in the posttest.

These results show that most of the participants from both research groups gained scientific knowledge during their study using the standard curriculum, but success in the posttest was predicted only for participants who studied through the CC1 with the NetLogo L2C model interactions.

Table 4
Comparing participants' accuracy of responses in posttest.

	Group 1		Group 2		t
	M	SD	M	SD	
Total	66%	6.4	77%	9.2	0.004
Multiple choice	71%	7.4	83%	9.8	0.009
Open-ended	33%	2.2	46%	10.2	0.003
Diffusion	62%	10.3	73%	10.0	0.020
Pressure	16%	8.4	24%	18.8	–
Atmospheric pressure and gravitational force	22%	8.8	41%	14.4	0.002

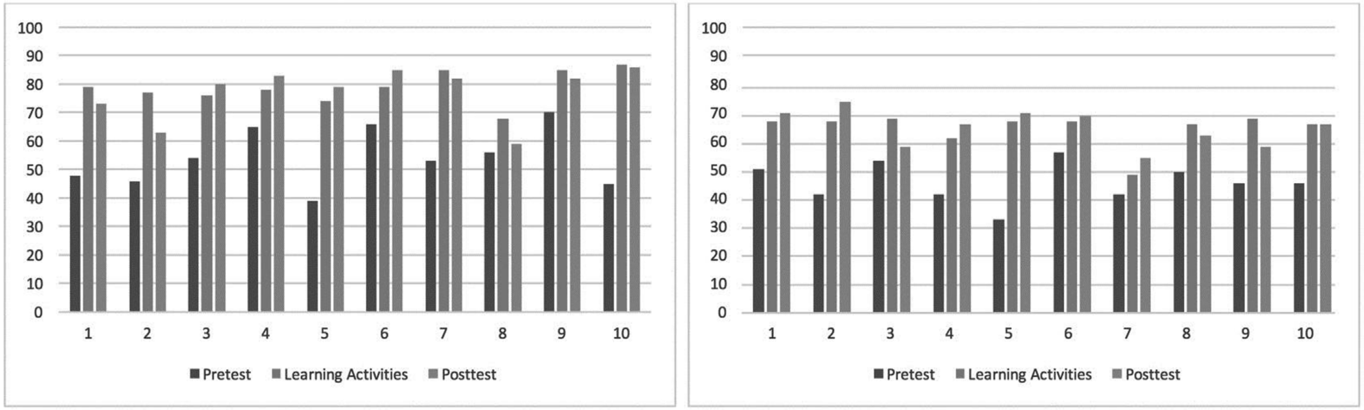

Fig. 3. L2C participants' accuracy of responses in the pretest, posttest, and learning activities (left) and accessible learning curriculum participants' accuracy of responses in the pretest, posttest, and learning activities (right).

4. Discussion

This research aimed to explore if and how participants who are blind perceive sound streams and transform them into scientific conceptual thought through interactions with L2C systems, and to compare the science learning of learners who are blind who followed a standard learning curriculum-based textbook to that of those who followed an identical curriculum with added interactions based on the L2C agent-based model. The results reveal that both experimental research groups gained scientific learning and that the sonified model interactions provide enhanced access to central and difficult scientific concepts, even when the target phenomenon is complex. These results may encourage the embedding of accessible standard sonified learning materials in the K–12 curriculum, leading to improvement in the integration of students who are blind in general education schools.

This discussion focuses on three issues: sonified explorations of complex phenomena; sonified explorations that lead to scientific learning and understanding of complex systems, possibly compensating for the inability of students who are blind to perform hands-on visual exploration; and a CC1-based textbook that enables participants who are blind to acquire scientific knowledge.

4.1. Sonified explorations of complex phenomena

The auditory channel is one of the main compensatory modalities for people who are blind. The L2C model interactions assist the learner who is blind to hear several audio streams and to integrate them into a complete scientific concept. The participants were able to hear the "visual scenario" and through it to learn and understand complex scientific phenomena. In this research, the participants needed to detect two to five auditory streams simultaneously. This detection is a cognitively demanding process, requiring the identification of each stream and then the integration of all information into one combined representation. Stifelman (1994) has demonstrated that this gradual exposure aids in building stream segregation, allowing an increase of the number of perceived channels beyond three. In this research, to aid the participants, we provided gradual exposure to the audio streams to enhance auditory segregation, improving perception and identification of different sonified representations. With this gradual exposure, the participants were able to detect five auditory streams simultaneously. The participants learned to detect the sonified feedback as part of the L2C activities, without a training process. A longer period of learning through a sonified system might improve their auditory skills and learning ability.

4.2. Science information can be collected via sonified feedback

This is the first study in which participants who are blind have been able to access information in exploratory science learning using sonified feedback. The learning through the sonified activities is represented in the results; the participants who studied using the L2C sonified system gained a higher level of understanding both in science content and in understanding systems compared to those who studied using only the CC1-based textbook. Significant results were found in the learning activities with embedded L2C interactions. Comparison of responses to each question after a L2C interaction indicated a higher average accuracy in the L2C group. As found by De Oliveira et al. (2017) and Supalo et al. (2016) the interaction and engagement through hands-on activities in the STEM curriculum enhance the learning of students who are blind. Similar results were found by Scalise et al. (2018), suggesting the integration of digital interactive STEM simulation to ensure accessibility for people who are blind. Here the L2C sonified interactions serve as a hands-on learning activity providing access to learning for students who are blind, resembling the learning process of students with sight, who are able to interact and engage in hands-on activities in the STEM curriculum. Our results followed Samon and Levy (2011) research results with sighted participants; they showed that sighted students scored higher after learning with NetLogo agent-based models, particularly when micro- and macrolevel behaviors were distinct. Learning the molecular descriptions of physical phenomena and understanding the random behavior of gas particles is difficult (Nussbaum, 1985; Westbrook & Marek, 1991). In understanding a complex system, its stochastic nature and "thinking in levels" are both challenging and central to reasoning (Jacobson, 2001). The CC1 started with an activity that was based on the participants' former knowledge, and with this knowledge they were able to learn new terms and to construct understanding of scientific phenomena. Through the CC1 curriculum, in which the L2C interactions were embedded, two scientific concepts were learned: random behavior of gas particles and incorporation of a particulate view in making sense of a physical system. These terms are central to understanding both science content (Johnstone, 1993) and systems (Bar-Yam, 1997). In this study, the learning process through the L2C agent-based model interactions did not greatly extend the learning period. Actually, those who learned through the L2C models needed a shorter time in reading and answering the questions in CC1.

4.3. Learning through accessible learning materials

The ability to learn through accessible standard learning materials is one of the keys in assisting students who are blind to be integrated in the K–12 education system and in higher education (Mani, 1998). Research has suggested enabling students who are blind to learn science through accessible standard learning materials by using tactile images, specific instructions, and hands-on learning experiences (AAAS, 1991; Dick & Kubiak, 1997; Kumar et al., 2001; and; Toenders et al., 2017a). As found by Klingenberg et al. (2012) studying using accessible materials enables students who are blind to learn independently on an equal basis with their sighted peers. Following these suggestions, we altered the CC1 to render it accessible. Comparison of the pre- and posttest results for the CC1-based textbook experimental group shows significant results in the participants' achievements. The participants were able to collect and acquire science knowledge as a result of their learning process using the accessible curriculum, as demonstrated in their answers to multiple-choice and open-ended questions, and later in their posttest responses. But access to learning through exploratory activities with the addition of L2C models interactions further enhances understanding and learning of complex systems for students who are blind.

5. Conclusion

These research results have important implications for continuation of the research and also for implementation. Regarding research, further studies might focus on new multimodality learning support tools for sighted students or students with special needs (such as dyslexia, text reading difficulties), and their ability to collect and understand information through the integration of various sensory modalities (visual and auditory versus visual only). Future research should compare the relative benefits of learning CC1 for sighted participants or people with special needs through sonified feedback (via L2C models), sonified and visual feedback (via L2C models), and visual feedback (via the NetLogo system). Figueiras and Arcavi (2014), who examined learning tools that are used in visually impaired classrooms, suggested using these tactile and auditory modalities tools to support the mathematics learning process for sighted students as well. The underlying idea is to create one more path to transfer knowledge; sighted students whose visual modality is weak can improve their learning ability using other modalities, such as sonified interactions.

The results of this research and that of Samon and Levy (2011) point to the need for further studies that compare scientific learning ability by students, both blind and sighted who are studying through the same L2C models. The L2C models include visual and sonified feedback; students who are blind can make use of the sonified feedback and sighted students can employ the visual feedback or both sonified and visual feedback.

Following these research results, other studies should focus on the effect of time exposure while learning through a sonified system. This learning process is cognitively demanding, requiring the identification of each stream followed by the integration of all information into one combined representation. In our research the participants were able to integrate five auditory streams simultaneously. We assume that a longer time exposure would improve their auditory skills and learning ability and would allow them to identify and integrate more than five sonified streams.

For implementation, sonified feedback such as L2C agent-based models can be implemented in K–12 or higher education, or as an assistive tool allowing access to visual information by multimodality learning support tools for sighted students, people who are blind, and other children with special needs (Figueiras & Arcavi, 2014). Douglas (2001) supported the use of assistive technologies by students who are blind to allow them equal opportunity to be integrated in public schools. The accessible standard learning materials, with or without L2C sonified NetLogo models developed for this research, could play a central role in STEM education for students who are blind and for their independent integration in general education schools, placing them on an equal basis with students with sight. The research results highlight the potential of integrating students who are blind with sighted students in STEM curriculum study. The L2C models include visual and sonified feedbacks, which allow students who are blind and sighted to work together with the same model at the same time.

This approach should include providing accessible standard learning materials for students who are blind in STEM and other curricular areas. Design and development of a NetLogo L2C library based on sonified feedback from these developed sonified models will enable inclusion in other STEM curricula. It will allow teachers to use adaptive learning materials without the need to expend valuable time and effort, which are already spread thin (Toenders et al., 2017b). Teacher training will be needed to effectively implement the NetLogo L2C sonified model in an integrated classroom, and, in the future, trained teachers should be able to design additional new sonified models independently.

Sonified audio graphs can also be integrated in other areas, as an assistive tool allowing access to a static graph. For example, access to digital newspaper, articles, and other learning materials, which integrate a static graph (e.g., in mathematics education, statistics, or economics).

The L2C agent-based model has some challenges or limitations. First, the L2C models are based on the NetLogo library, whose models focus mostly on STEM education, although this library is continuing to grow. Secondly, each agent-based model represents only one scientific phenomenon, for example the CC1 included three L2C models: experimenting with particles, pressure, changing pressure (Fig. 2a and b), diffusion (Fig. 2c), and atmospheric pressure and gravitational force (Fig. 2d). Third, there is a need to develop a simple editor, which will allow the teacher to create new L2C models for students who are blind in a short time. The forth limitation involves the dependency of the learning materials on the phenomena they depict, requiring a dynamic phenomenon such as the sound. It will be much more difficult to use sonified simulation to study static artifacts such as in art. Static artifact (e.g., a painting) has extensive visual information that is integrated in one "view" (shapes, colors, space, depth, etc.). Of concern, also is the number of auditory streams that the user can receive simultaneously and still be able to construct a cognitive concept of a whole representation. Stifelman (1994) has demonstrated that gradual exposure aids in building stream segregation, thus enabling participants to increase the number of perceived channels beyond three. In this research the participants were able to identify and construct a cognitive concept of four and five sounds and varied sound streams (events and audio graphs).

Despite these limitations, the research results show promise for improving achievement in science for students who are blind, and follow-up research and implementation should prove beneficial.

Acknowledgments

This research was partially supported by a grant from The Israel Science Foundation (ISF) (Grant No. 536/11). We thank our anonymous participants for their time, efforts, and ideas.

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.compedu.2018.08.020.

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