Title:

Listening to or Looking at Models: Learning about Dynamic Complex Systems in Science among Learners who are Blind and Learners who are Sighted

Running title:

Listening versus Looking

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Authors contribution statement:

STL and OL acquired financial support for the project. All authors conceived and designed the project. RP and NH acquired the data. RP, STL analysed and interpreted the data. RP, STL and OL wrote the paper.

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There are no known conflicts of interest.

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Practitioner Notes:

What is already known: Sonification is the addition of non-speech sounds that represent dynamic information. Sonification can be used to allow equitable participation for students who are blind.

What this paper adds: The study compared learning of students who are blind using a sonified learning environment (L2C) to that of students who are sighted using a visual environment.

Implications for practice: Students who are blind showed equal or better learning using the sonified L2C models compared with students who are sighted using visual models. There are major implications for integrating students who are blind in public school classrooms.

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Abstract:

Background: Students who are blind are integrated into public schools in many countries, yet are often excluded from full participation in science since most learning materials are visual. To create a compensatory route, an existing model-based inquiry-learning environment was adapted by means of sonification (addition of non-speech sounds that represent dynamic information). The learning environment uses agent-based models and a complex systems approach to teach the Kinetic Molecular Theory and Gas Laws. The models are accompanied by a workbook consisting of text (printed or auditory) and images (printed or tactile).

Objectives: The current research examined whether such perceptual compensation creates a comparable learning environment for learners who are blind compared with learners who are sighted using the original learning environment. The aim of the study is to expand knowledge about how the auditory channel may compensate the visual channel among individuals who are blind.

Methods: Conceptual learning in science and reasoning about complex systems were assessed using pre- and post-questionnaires. To explore learners' learning progression throughout the unit, four progression analysis “windows” were selected. These were groups of adjacent or nearly adjacent items in the workbook that permitted a glimpse of learners' progression.

Results: The sonified environment not only supported the learning of learners who are blind compared with the learning of learners who are sighted using visual material, but even furthered their learning with respect to diffusion, one of the more challenging concepts in Kinetic Molecular Theory. It seems the types of sonified representations used in this study increased listeners’ sensitivity to the micro-level interactions in a way less accessible in visual representations.

Takeaways: Sonified environments can be provide learners who are blind with equitable participation by compensating and complementing the visual channel. Sonification can have implications for students who are blind as well as students who are sighted.

Keywords:
Science learning; Sonification; Agent-based models; Complex systems; Blind

1. Introduction

How can we support students who are blind in gaining access to exploratory learning materials in science?

Students who are blind have been integrated into public schools for decades in many countries such as Israel. Despite this, most learning materials in science education are based on visual information, thus disadvantaging students who are blind (Beck-Winchatz & Riccobono, 2008). One specific area which has traditionally relied heavily on visualization are models and simulations. These allow learners to manipulate, explore and discovering patterns in the world as a main avenue to science learning (de Jong & van Joolingen, 1998). Several literature reviews have shown that there is robust evidence that models and simulations can significantly enhance other forms of instruction in science (Louca & Zacharia, 2012; Rutten et al., 2012; Smetana & Bell, 2012), and learning environments developed in the past two decades, progressively include such model-based learning as an essential component of the curriculum.

Listening to Complexity (L2C) is an environment that seeks to provide access to model-based learning to students who are blind and their teachers: thus striving to provide equal access to the science classroom. Its design is based on the assumption that the supply of appropriate information through compensatory sensory channels may contribute to learning among students who are blind (Passini & Proulx, 1988), and this supply of information is provided by means of sonification (non-speech audio which represents certain information). The environment allows full interactions with exploratory materials, independent collection of data and controlling their learning process.

This paper focuses on this model-based inquiry-learning environment adapted for learners who are totally blind without residual vision. The model uses a complex approach to learning using an agent-based model. These terms will be investigated in more details in the literature review. Specifically the paper investigates whether the sonified agent based model for learners who are blind can provide a comparable alternative to the original agent based model for learners who are sighted.

2. Literature Review

2.1. Complex system approach to teaching

Complex systems approaches have come into the limelight in several different domains of science and in education and are based on the following idea: a system can be modelled as many entities that operate according to a small set of simple rules, their concurrent actions and interactions emerging into global patterns (Bar-Yam, 1997). The complex systems approach focuses on how local behaviours and interactions of single entities form a global pattern and can contribute to a wide array of systemic phenomena (Barabasi & Bonabeau, 2003; Nicolis & Prigogine, 1989; Turchin, 2003). This research aligns with the US framework for science education (National Research Council, 2013) that underscores systems and models as central crosscutting concepts.

A complex systems approach to teaching chemistry has been shown to help students overcome these obstacles (Holbert & Wilensky, 2014; Levy & Wilensky, 2009b). One way of introducing students to dynamic complex systems is by means of agent-based modeling (ABM) in which a computer model simulates the many autonomous, interacting entities of the system, allowing the user to observe how global patterns develop from interactions between individual entities.

NetLogo (Wilensky, 1999b) is a freely downloadable modelling environment that enables the use of ABM. In this study, the models are based on the GasLab (Wilensky, 1999a) and the Connected Chemistry (CC1) (Levy & Wilensky, 2009a) curricula which enable learning about chemical systems at both the observable macro- and molecular micro-levels. Previous research with sighted students using these environments indicated significant learning gains in conceptual understanding of the behaviour of gas particles and how this behaviour influences global observable phenomena (Levy & Wilensky, 2009b; Samon & Levy, 2017)

2.2. Assistive technology for students who are blind

Students who are blind have been integrated into public schools for decades. Thus, their science learning is usually supported by the science teachers and not by specialists. However, since most learning materials in science are based on visual information, science education fails to provide inclusion for students who are blind (Beck-Winchatz & Riccobono, 2008). Only few specialized manuals and learning environments have been created to teach science to students who are blind (e.g.

Willoughby & Duffy, 1989). Assistive technologies can bridge this gap by providing an alternative route to accessing information.

Assistive technology systems in science education are rare, due in part to the unique symbols, characters, and nonlinear writing styles used (Nees & Berry, 2013; Power & Jürgensen, 2010). Past examples include Talking Tactile Tablets that use audio and 2D tactile images for learning mathematics and science diagrams (Landau et al., 2003), a haptic simulation that allows elementary and secondary students who are blind to learn about particle motion, temperature, and pressure (Jones et al., 2014), Line Graphs technology based on auditory and haptic feedback geared to learning mathematics (Ramloll et al., 2000) and the force-feedback mouse in physics education (Farrell et al., 2001). These examples require special hardware to deploy, which might not be easily accessible to every science teacher.

The assistive technology used to aid the learning of people who are blind are based on tactile (such as braille screens) and/or auditory modalities (such as screen readers). The advantage of the later is that it often does not require specialized hardware. Auditory output can be produced by common computers whereas tactile output requires specialized equipment such as braille screens or haptic feedback devices. The auditory modality aims to compensate for lack of visual information by providing information in speech (such as screen-readers) or sonification which are non-speech sounds (Kramer, 1994). Presentation of information in speech is suitable for texts whilst sonification is more suitable to provide non-speech information such as spatial and temporal information (Katz & Picinali, 2011; Leuders, 2015; Sánchez et al., 2008). Examples of sonification could be the beeps on a heart monitor, the siren of a police car or an audio-graph that represents the amount of carbon dioxide in the atmosphere by changes in pitch (see for example this video that sonifies the levels of carbon dioxide in the atmosphere over time - https://www.youtube.com/watch?v=O5AhP1I61sU).

2.3. The L2C environment

The L2C environment uses a complex systems approach and ABM to teach students about Kinetic Molecular Theory (KMT) and Gas Laws, theories fundamental to the understanding of many advanced concepts in the physical sciences (NGSS by the National Research Council, 2013). One of the challenges of gaining a well-developed understanding is that chemical systems can be described in at least three different modes: an invisible molecular sub-microscopic level, an experienced macroscopic level and symbolic representations (Johnstone, 1993). Research has shown that students often lack deep understanding of all three modes (Nussbaum, 1985).

To this goal, an existing model-based inquiry-learning environment (Levy & Wilensky, 2009a, 2009b; Samon & Levy, 2017) was adapted for learners who are blind by means of sonification, the use of non-speech audio to convey information (Kramer, 1994). Sonified interfaces can utilize at least five of seven principles of universal design: (1) appropriate use; (2) flexible usability; (3) simple, intuitive use; (4) accessible and easy to remember information; and (5) resistance to mistakes (McGuire et al., 2006).

The L2C models enable users to interact with dynamic objects that are computed in real time, providing a heightened sense of reality while learning about complex scientific phenomena. The sonified representation of dynamic complex systems, provides access to quickly changing information of both micro- and macro-levels in a system. Important for future dissemination and viable equity, it is a low-cost technology based on the robust and continually-developing free NetLogo platform (Wilensky, 1999b). Also, sound is conveyed by simple headphones in stereo, which by adjusting the volume and the relative volume between the two earpieces allows for a 2D representation of the particles. Following the authors' original work (Lahav & Levy, 2011; Levy & Lahav, 2012), PhET, a University of Colorado based project specializing in interactive simulations, has started developing similar sonified models (Moore, 2015; PhET, n.d.; Tomlinson et al., 2019, 2021; Winters et al., 2019).

This research paper builds on a long process of research and development work by the Authors and their colleagues. As a first step the viability of the sonification approach was investigated by developing and testing ways in which models with sound mediation can support science learning by blind people (Lahav & Levy, 2011; Levy & Lahav, 2012). Based on this work, later studies refined these models by investigating blind participants' auditory perception of varying types of auditory representations and complex sound patterns. This allowed for a better understanding of the process by which sound patterns are perceived and transformed into a conceptual model (Lahav et al., 2017, 2019). More details can be found in previous publications. In brief, the resulting environment sounds were related in semantics to their referent; for instance particle collisions were sonified by the collisions of two billiard balls. Sound effects that are readily produced by common computers were used to allow for easy transferability. Going through the L2C learning activities, users are progressively exposed to two to five sound streams which helps build stream segregation by the user. The following video-link demonstrates the sonified learning environment (https://www.youtube.com/watch?v=BQpM-oM7hI8). The main technology used to develop the sonified representations was the NetLogo platform (Wilensky, 1999) for modeling systems. We also used an extension to NetLogo that we developed for making the sound output stereo and more precise in handling sound files. Finally, the computer’s MIDI sound system and external wav files were employed.

Building on these refined sonified models, the next step was to compare how the L2C system would fare compared with existing teaching methods amongst learners who are blind (Lahav et al., 2018). Twenty people who are blind were split into two groups (participants were aged 17–33; fourteen were undergraduate students, two were high-school students and the rest were not enrolled in an educational programme). All participants were selected using criteria set by a local organization for the blind that also helped recruit the participant. All participants had studied science in school, but not at college or university. None of the participants studied Kinetic Molecular Theory (KMT) of gas previously. One group studied using a curriculum-based textbook and the other using an identical curriculum integrated with L2C. Participants who used the L2C models outperformed their peers, thus supporting the sonification approach as a compensatory aid that allows hands-on learning experience for learners who are blind.

Thus far, this body of work was conducted only with people who are blind to examine the design of the learning environment and their related perceptual, cognitive and learning processes. Adding to this body of work and going beyond it, the present study includes sighted individuals who learn with more typical visual simulations and compares their learning with that of learners who are blind. We compare learning outcomes and processes for a set of curricular materials in a sonified mode among learners who are blind and a visual model among learners who are sighted. The study serves to expand knowledge about how the auditory channel may compensate and complement the visual channel among blind individuals for learning complex systems in science. On a practical level the study helps understand how curricular materials can be adapted for classes in which both students who are sighted and students who are blind study together.

To summarise, in this study we wish to examine whether sonification for people who are blind can compensate for the visual cues in a learning environment based on a complex systems approach. We assess both conceptual learning in science and reasoning about complex systems among learners who are blind and learners who are sighted with guided exploration of an ABM learning environment in which micro- and macro-level variables and events are either visual or sonified. Our research question is: How do conceptual learning, systems reasoning and learning processes with sonified feedback for learners who are blind compare with learning through visual feedback for learners who are sighted?

3. Methods and materials

3.1. Research Design and Participants

To investigate the comparative learning of learners who are blind and learners who are sighted a two-group pre-test - intervention - post-test quasi-experimental design was used. For those less familiar with research in special education, it is important to know that students who are blind or visually-impaired are a rare population (3% of children 18 years and younger; CDC, 2020) and much effort was put into recruiting each and every one of them. Participants were recruited with the help of organisations for the blind and also through snowball sampling. Constant communication with the participant was needed to ensure that mobility issues would not be a hinderance. No awards or incentives were offered participants.

It is important to note that research that compares blind and sighted people is rare because of the difficulties in obtaining participation of blind people. One alternative research approach is to replace blind people with sighted individuals who have their eyes blindfolded (see for e.g. Law & Vanderheiden, 1999, 2000). In our view (shared with others s.a. Bennett & Rosner, 2019; Tigwell, 2021), this is an inappropriate choice in terms of additional issues that come with being blind, such as a heightened use of alternative sensory modalities, expertise in finding alternative ways to compensate for lack of sight and experience in using technology without sight and more. Thus, the decision made in this project was to engage people who are blind. The price to pay for that decision is non-equivalence between the two research populations. It is very hard to obtain participation of blind people because many are not mobile, and so the criteria for inclusion in the study had to be loosened, resulting in a difference in average age and sample size. Thus, the experimental group consisted of ten participants who are blind. The comparison group consisted of 31 seventh grade students (aged 12 to 13) who are sighted who attend a high socioeconomic school.

To compensate for this non-equivalence in age, the learning unit that was selected for the study is well tested and has been used with a range of ages from seventh (Samon & Levy, 2017) to eleventh grade (Levy & Wilensky, 2009a, 2009b) and was found challenging and engaging at the different levels of education. Moreover, in our earlier research with adults who are blind (Lahav & Levy, 2011), we could see strong learning gains, similar to that of the students in the present study.

The participants who are blind were selected based on three criteria: totally blind without residual vision, no additional disabilities, and no previous learning of the KMT of gases. These criteria were verified by participants' self-reports and by representatives of organizations for the blind, who aided us in recruiting them. They were aged 19–28, M = 24, SD = 2.68; nine were male and one female; nine were congenitally blind; and three had residual vision (light perception). Eight were undergraduate students, and two worked in a factory. 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. All participants knew how to operate computers for daily use. Although most participants read and wrote braille, during the research sessions, all participants preferred to use an auditory explanation file and tactile images (pre- and post-test questionnaires and workbook guide). Participants were recruited with the help of organizations for the blind and through snowball sampling. All participants gave their consent prior to starting the study. They could withdraw from the study at any point. Withdrawal would not effect their right to continue learning with the unit.

The participants who are sighted were students in two middle school science classes. All were in the 7th grade (normally aged 11-12) and were distributed roughly evenly between genders.

An ethics approval for the research was obtained by the Israel’s Ministry of Education and the University Ethics Committee. For the sighted students, an initial permission to run the unit and collect data was obtained by the vice-principal of the school. A few days before running the unit, a letter was sent to parents in which they could opt-out their child from participating in the data collection. Students could also choose to withdraw from the study at any point without consequences. Students who did not participate in the data collection still participated in the teaching and learning activities. No personal data (such as age or gender) was collected. It was made sure that names were kept separate from the data and that the teachers had no access to the data. In order to match pre-questionnaires, post-questionnaires and responses on the workbook in an anonymous manner, students were given a unique identity number. This number was available to the researcher only during the sessions. It was kept in a secured and separate file from the questionnaires and destroyed at the end of data collection. In the school, neither the teacher nor the school administration had access to the file of identity numbers

3.2. The L2C Learning Environment

The L2C (Listening to Complexity) learning environment is made up of a guide (workbook) and a suite of models. The guide presents new concepts, explains the use of technologies, and directs the activities. The models were created with NetLogo (Wilensky, 1999b), onto which a locally-created extension that supports the use of stereo and sound files was added (Figure 1). The models were adapted from models that had been developed previously - GasLab (Wilensky, 1999a) and Connected Chemistry (CC1) (Levy & Wilensky, 2009a). These models include a microscopic representation of a gas in a container in the form of particles (points) located within a rectangle (representing a vessel). The suite of models allows learners to gradually learn about gases and Kinetic Molecular Theory (KMT), and then conduct inquiry to learn about basic gas laws. A key element in the curriculum is to develop learners’ epistemologies of modelling, which is an important aspect to support learners’ conceptual learning (Levy & Lahav, 2012; Levy & Wilensky, 2009a, 2009b). With each additional model learners explore a new function, which allows them to discover a new characteristic of the nature of gases as detailed in the curriculum (Table 2). Table 1 describes the sonification framework used to adapt the models for learners who are blind and compares it with the visual representation the sighted students used. The sounds were selected after extensive research with people who are blind regarding their preferences, their ability to discern the sounds with as many streams as possible, and ability to convert them into meaningful information (Lahav et al., 2017, 2022).

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Central to the L2C curriculum is a workbook consisting of eight activities (Table 2). It is based on two earlier curricula (Levy & Wilensky, 2009a, 2009b; Samon & Levy, 2017) and includes guided exploration of the agent-based computer models, short laboratory demonstrations and class discussions. For most of the unit, learners can progress at their own rate with the workbook providing guiding information and questions.

3.3. Data Sources

For both the learners who are blind and sighted, data were collected from two sources: (1) learners’ responses to pre-post questionnaires and (2) selected workbook items. In both groups each student was given a unique identifying number.

3.3.1. Questionnaire

A pre-post questionnaire was developed as to align with the curriculum (Shavelson et al., 2003; questionnaire available in the supplementary materials). This was done through a two-stage analysis:

(1) Stage 1 – Characterization of the curriculum.

Each of the 229 items question in the workbook was characterized according to four dimensions:

a) Open-closed
b) Topic in the curriculum. The following topics were included: The Kinetic Molecular Theory (KMT), pressure (P), the number of particles’ effect on pressure (N-P), changes in volume and their effect on pressure (P-V), temperature (T), effects of temperature on pressure (P-T), effects of the number of particles on pressure and volume (N-P-V), relationship between number of particles, pressure, volume and temperature (IGL), diffusion (D), atmospheric gases – effects of gravity on the air particles’ density and pressure (ATM).

c) Systems components used for a correct explanation: microscopic level, macroscopic level, microscopic level affecting the macroscopic, macroscopic level affecting the microscopic level, the bridge between microscopic and macroscopic levels

d) Level of knowledge normally used to determine science achievement: Declarative, Procedural, Schematic, Strategic. The definitions followed (Shavelson et al., 2003). When coding for this we asked the question "What type of knowledge does the student need to employ in order to answer this question?":

   Declarative – Anything that was recall of something stated before in the workbook

   Procedural – A question requiring the employment of skills the student already has or developed previously in the workbook (reading the model, reading the graph, making observations).

   Schematic – Shavelson et al.’s (2003) definition of schematic knowledge relates to “knowing why”. To know why requires a mental representation of a scientific model or concept. Hence every question that necessitated applying a mental model was marked as schematic.

   Strategic – Questions requiring to know which type of the above categorized knowledge had to be recalled and used. A question requiring 'meta' thinking

(2) Stage 2 – Constructing the questionnaire to assess learning with the curriculum.

A bank of questions was gathered. Most items were used and validated in previous research (Levy & Wilensky, 2009b; Samon & Levy, 2017). Additional questions were gathered from the literature or made up. This bank of questions was characterized as in stage 1. A questionnaire was then conceived so that the questions represented similar proportions for each of the dimensions in stage 1. For example, if 26% of the 229 workbook questions required procedural knowledge, in the final questionnaire 5 of the 20 questions (25%) required procedural knowledge to be answered. In this case, a very close fit was obtained between the proportions in the workbook and the questionnaire. On other instances the fit wasn't as close, but it was always in the range of about 10 percent.

Finally, the questionnaire was printed in four differently-ordered versions to avoid biases resulting from question order.

3.3.2. Progression Analysis Windows

To explore learners' learning progression throughout the unit, four “windows” were selected (hence, progression analysis windows). These were groups of adjacent or nearly adjacent items in the workbook that permitted a glimpse of the learners' progression. The items were chosen with the following criteria in mind (Table 2):

(1) The windows should be spread out fairly equally across the unit.
(2) The items in each window should consist of open and closed items mirroring different levels of difficulty.
(3) The items elicited rich explanations of the system’s behaviours.

3.4. Procedure

The participants who are blind worked and were observed individually. Each session lasted 60 minutes, and the research consisted of ten sessions that were distributed over 5-8 weeks. The participants who are sighted worked in their school’s computer lab, 1-2 students to a computer, during four double-periods over two weeks. The teacher and researchers conducted few conversations, mainly to support students’ understanding of the workbook instructions. Both groups completed identical pre- and post-test questionnaires (included in the supplementary materials).

3.5. Analysis and coding schemes

Some of the data of the participants who are sighted was excluded from the analysis (seven individuals leaving a sample of n=24) since they failed to complete at least a quarter of either pre- or post- questionnaires (i.e. less than 18/24 questionnaire items) or since their workbook was almost completely empty indicating they did not engage with the curriculum.

Three types of analyses were conducted:

1) Overall learning gains: An overall score for each pre- and post-questionnaire item was calculated by awarding 1 point for each correct answer. From this data, overall learning gains for each student were calculated using the formula: $\text{Learning Gain} = (\text{post score} - \text{pre score})$. The aggregated learning gains of the participants who are blind and the participants who are sighted were compared with nonparametric statistics, due to the small sample size of the participants who are blind.

2) *Learning of different scientific concepts and of systems learning*:

A coding scheme (Table 3) was developed based on schemes developed in previous studies (Levy & Wilensky, 2009b; Samon & Levy, 2017). Questionnaire items were categorized according to the scientific concepts and the ideas of systems thinking they incorporate. The same item could incorporate more than one scientific concept and/or idea of systems thinking. Each student was given a score for each scientific concept and each idea in systems thinking. The scores of the participants who are blind and sighted were compared (Table 5).

3) *Learning progression*: The learning progression was analysed by in-depth analysis of the four progression analysis windows in the workbook. A deeper analysis of the items was conducted for the learning progression which included coding for both scientific content as well as systems thinking approach (Table 4).

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3.6. Validity and Reliability

As mentioned above, most of the questionnaire items used and validated in previous research (Levy & Wilensky, 2009b; Samon & Levy, 2017) supporting the questionnaire's construct and criterion validity. The questionnaire was also reviewed by five middle school science teachers. All confirmed that the test items were appropriate for examining the issues studied in the two learning environments.

The assessments were checked by the researchers. Comparison of the independent scores and codes yielded 97% agreement on 2,208 items. Disagreements were resolved uniformly by discussion.

4. Findings

The findings relate to two analyses: learning gains of the pre-test and post-test scores, and the learning progression through the analysis window of participants' workbooks.

4.1. Learning Gains

Pre-test scores did not differ significantly for the participants who are blind and sighted (Mann-Whitney U=136, p=0.539). No significant differences were found between the learning gains of the two groups, but the post scores of the participants who are blind were significantly higher than those of the students who are sighted (Table 5). Both groups demonstrated an overall rise in group scores from pre- to post-tests (comparing pre to post scores: for the participants who are sighted - Mann-Whitney U=288, p<0.005; for participants who are blind - Mann-Whitney U=50, p<0.001).

With respect to specific science concepts that were learned, the participants who are sighted mainly demonstrated increased scores in the learning of Gas Laws, KMT and density to a certain degree and regressed with respect to understanding diffusion. The learning gains for participants who are blind were significantly higher than those of the participants who are sighted for KMT and diffusion. No differences were found in the learning gains for the different systems components between the groups. In summary, the sonified representation supported the learning of the participants who are blind in a comparable way to that of the learning of participants who are sighted and was even related to greater learning of KMT, the micro-level theory of the system, and diffusion, a challenging concept.

4.2. Learning progressions

The processes of learning were evaluated along four time windows for both groups. This was analysed in three ways: according to components of systems thinking, according to three of the scientific concepts and according to a number of specific scientific concepts. The graphs of the learning progressions for the different concepts have different shapes, based on whether the concept is accessible to the student, whether it is relevant to use that concept in the specific activity and whether there is an opportunity to express the concept. This analysis resulted in 38 graphs in total which were analysed for similar themes or patterns. For brevity, in the main text of the paper we show graphs that are representative of each theme (Figures 2-4). Figures including all graphs can be found in the supplementary materials (Figures S1 and S2).

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Comparing the temporal curves for the categories of systems thinking shows that for most concepts (micro thinking, macro thinking, slippage, dynamic equilibrium and emergence) the learning process was similar for both groups (Figure 2 (i)). This was not true for agents' interactions, uncertainty, dynamic equilibrium and decentralized control (Figure 2 (ii)), where the participants who are blind provided more of these explanations earlier in the learning process.

When comparing the temporal curves for three main scientific concepts the differences are small or none (Figure 3). It is worth noting that while large differences were seen between the post-test results for KMT between the two groups, these differences are not evident in the learning progression. Similarly much learning of diffusion was seen among the participants who are blind in the post-test, yet this is not evident in the sampled learning windows since diffusion is only introduced in the textbook after analysis window T3 and analysis window T4 does not directly discuss diffusion.

KMT requires greater understanding of the micro level. When looking into the specific scientific explanations the greatest differences between the two groups were those that involved complex micro-level thinking (see Figure 4(i)) namely that gases are composed of particles, particles move in straight lines, particles collide with one another, particles collide with the walls of the vessel containing the gas, particles do not change their speed upon collision with a wall, particles change direction upon collision with one another, particles change speed upon collision with one another, particles move in random directions and particles scatter around the room). One exception is the explanation of "Particles change direction upon collision with a wall" (Figure 4 (ii)). It seems that the sonification does not convey this clearly. Explanations relating to the macro level showed little difference between the groups.

5. Discussion & Significance

This study aimed to compare the use of sonified computer models by learners who are blind to the use of visual models by learners who are sighted. Two important findings emerged from the data. Firstly, the L2C environment can support learners who are blind in a comparable way to learners who are sighted. Secondly, learning of certain concepts was better or faster using the sonified environment. These points are elaborated below.

This study demonstrated that the L2C environment fully compensates for the lack of access to visual information among learners who are blind as they learn about a complex system, the gaseous phase of matter, and supports comparable learning provided by dynamic computer models for learners who are sighted. By enabling learners who are blind to engage with manipulable explorations of microworlds, inquiry learning becomes possible, a more robust form of learning, which is based on well-established constructivist theory. Given the success of this low-cost learning environment, extending this design to learning of other STEM systems by using sonified models opens the way to equitable participation of blind people. Future research might focus on whether these findings can be repeated with other sonified learning environments (such as those offered by PhET, n.d.) and in authentic classroom contexts.

In terms of individual concepts learnt, the sonified representation not only supported the learning of the learners who are blind in a comparable way to the learning of learners who are sighted using similar visual materials, but was even related to greater learning of KMT, the underlying particles behaviours and diffusion, all very challenging concepts. The learning progressions show that the individual science and systems concepts were learned at similar times, in correspondence with the learning materials. However, regarding the central systems concepts of interactions between individual particles, uncertainty, dynamic equilibrium, and decentralized control, the learners who are blind learned and applied these earlier.

Based on the earlier understanding of the central systems concepts and the deeper understanding of KMT of the learners who are blind, it would seem that L2C's sonified representations increase sensitivity to micro-level interactions (e.g. collisions) in a way that is less accessible in visual representations. We had chosen to sonify particular significant events for a single particle, on one hand, and the time progression of global variables such as pressure in the container, on the other hand. In fact, much information in the visual array is missing in the auditory array – the many other particles, each of which are moving about, colliding and bouncing off walls. It seems that filtering of information helps learners focus on these interactions that are subtle in an array of many particles, and notice their random changes over time, evidence from which uncertainty can be derived.

The participants who are blind, demonstrated a greater understanding of diffusion which is a widely misunderstood concept that is highly-resistible to change (Chi, 2005). This seems to be related to their understanding earlier on in the learning progression of some of the systems concepts. Systems concepts help make a clear separation between micro-level behaviours and macro-level patterns and provide a way to reconcile visible behaviours with particulate interactions (Samon & Levy, 2017). This difference was not seen in the learning progression mainly due to a limitation of the research tool (i.e. no question relating directly to diffusion).

An interesting question to follow up in future research would be whether the design of appropriate sonified materials for learners or students who are *sighted* may promote their learning of complex systems in a similar manner. Are certain scientific phenomena that are typically conveyed by sight be better conveyed by sound? If so, which ones and how can they be integrated into science teaching? Answering these questions would pave the way not only to a more inclusive way of teaching for students who are blind, but one that would benefit the student population as a whole.

This paper focused on the sonification of just one model-based learning environment based on a complex systems approach. Furthermore, it focused on specific (yet fundamental) science content. Work on the L2C has highlighted how reliant existing teaching materials are on the visual channel, and what can be gained if with relatively simple implementation and research, the auditory channel is engaged. This opens a whole range of opportunities – how can sonification be introduced into the teaching of other science topics or perhaps even other subjects?

A main limitation of this study is the discrepancy between the comparison and experimental group stemming from the limited availability of students who are blind people for this research. This resulted in different mean ages of the two groups and different learning conditions (school vs. post-school/university). This is an inevitable consequence of working with a rare population. The pre-test scores in our study were not significantly different, suggesting both groups had similar starting knowledge suggesting the findings would not differ in essence if we had comparable ages (with the caveat that although the pre-test scores were similar the peripheral background knowledge of older participants can affect performance and take up of knowledge). If we had younger participants who are blind, they might have been more playful leading to a slower learning progression (compared to adult participants who are possibly more ‘on task’). However, we believe the main findings of the study would be the same, namely that sonified environments can provide students who are blind with equitable participation and that sonified representations can increase learners’ sensitivity to the micro-level interactions. We hope this research can be extended to other countries to verify these results in other contexts and with more participants.

Another limitation of this research was that the participants who are blind participated in lab conditions. An interesting and relevant question would be how this activity would run in an integrated classroom where there are one or two students who are blind and all other students are sighted. The dynamics and interactions between the students using the different environments would make an interesting focus for future research. Following on from this, another interesting scope for investigation is how instructors who are blind could benefit from teaching students (who are blind and sighted) using this technology.

We hope this study will allow better accessibility and equity to the population of students who are blind by providing an insight to their learning using low-cost learning materials that do not require special hardware to deploy.

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Tables

Table 1: Comparison of the sonified and visual representations in the models used in the in the L2C Computer Model.

Events, Locations, Variables		Visual representation	Sonified representation[1]
Events	Collision: 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	One short sound: Billiard ball collision[2]
	Wall hit: 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	One short sound: Navajo drum[2]
	Entrance: Entry of new particles in the container	A semi-circle spread of dots starts from the box's opening	One short sound: Ping[2]
Location/Speed	Location: The location of a focus particle as it moves through the container; the rate of change in location also signifies speed	Full information is provided by placing a halo on the focus particle or have it leave a trail	Regularly intermittent sound every unit distance covered, so that greater rates signify a particle moving faster: Telephone busy signal[2]
Variable	Pressure	Plot of pressure versus time	Continuous sound: Bassoon[3]
	Temperature	Plot of temperature versus time	Continuous sound: Cello[3]

[1] All sounds were homogenous with con- current exposure (in which all sounds were played at the same volume 72-75 dB-SPL)

[2] Wav file recorded sound

[3] MIDI generated sound

Table 1. Learning Unit Overview showing the progression analysis windows

Activity	Details	Progression Analysis Windows
Pre-unit questionnaire	Students fill-in the pre-unit questionnaire	
Introduction	Students are shown three phenomena that relate to air pressure. They are asked what the three phenomena have in common and are asked to explain one phenomenon.	T1: 6 items, 5 open, 1 closed
Activity 1 *What is a model?*	The concept of scientific models is discussed. Students are shown a bicycle wheel, which will be modeled in NetLogo in the following activities.	
Activity 2 *The computerized model*	Students learn how to use the computerized NetLogo model and investigate the motion of particles in the model.	T2: 6 items, 3 open, 3 closed
Activity 3 *The Kinetic Molecular Theory*	The main principles of Kinetic Molecular Theory are introduced without a model. This activity summarizes activity 2.	
Activity 4 *Pressure*	By investigation students learn that pressure is caused by particles hitting a surface.	
Activity 5 *What effects pressure*	Students learn the effects of quantity of particles, volume and temperature on pressure. In effect they learn a qualitative version of the gas laws.	T3: 5 items, 1 open, 4 closed
Activity 6 *Diffusion*	Students learn about diffusion as a macroscopic phenomenon that can be explained by microscopic particle behavior.	
Activity 7 *Atmospheric pressure*	Students learn how pressure varies with altitude. This is an advanced activity meant for those students who excelled in the rest of the unit. Only few students reached this activity.	T4: 3 items, all open
Activity 8 Summary	Students are asked to refer to the three phenomena presented in the introduction and try to explain them using what they learnt	
Post-unit Post-test Questionnaire		

Table 2. Coding scheme for the closed questionnaire items

Category	**Description**
Scientific content	
KMT (Kinetic Molecular Theory)	Items relating to the particular nature of matter
Gas Laws	Items relating to macroscopic properties of gases and the correlations between them
Diffusion	Items relating to the phenomenon of diffusion
Density	Items relating to density.
Systems thinking	
Micro	Items relating to thinking on a microscopic level only
Macro	Items relating to thinking on a macroscopic level only
Micro to macro transitions	Items relating to linking between the microscopic and macroscopic levels

Table 3. Coding scheme for the workbook items included in the progression analysis windows

Scientific content
Gases are composed of particles
There are different types of particles
Particles move in straight lines
Particles collide with one another
Particles collide with the walls of the vessel containing the gas
Particles change direction upon collision with a wall
Particles do not change their speed upon collision with a wall
Particles change their speed upon collision with a wall (incorrect)
Particle change direction upon collision with one another
Particle change speed upon collision with one another
Particles move in random directions
Particles scatter around the room
Particles have no free will
Particles have a free will
Pressure is caused by particles colliding with the walls of the vessel
Reference to pressure in the macro level
Reference to volume in the macro level
Reference to density
Pressure is effected by the number of particles in the vessel (micro)
Pressure is effected by the quantity of gas in the vessel (macro)
Volume is effected by the quantity of gas in the vessel (macro)
Pressure is affected by changes in the volume of the vessel (macro)
Pressure is affected by changes in the volume of the vessel (micro with reference to particles)
Pressure changes with the temperature in the vessel
Diffusion as a macro phenomenon (gas moves from high to low concentrations)
Diffusion as a micro phenomenon (particles move freely and at random)
Ideas in systems thinking
Reference to the micro level
Reference to the macro level
Interaction between agents at the micro level
Emergence – Interactions at the microlevel cause the system to rearrange thus effecting macro behavior
Slippage between levels – use of language suitable for the micro level to describe the macro level (and vice versa)
Reference to centralized control
Reference to decentralized control
Uncertainty
Dynamic equilibrium

Table 4. Pre-test and Post-test Scores (%) and Learning Gain Comparisons for the Blind and Sighted Students, Overall, and by Concept

	Blind Students			**Sighted Students**			**Statistical analysis**		
Learning Concepts (# of items)	***Pre-test M (SD)***	***Post-test M (SD)***	***Learning Gain[1] M (SD)***	***Pre-test M (SD)***	***Post-test M (SD)***	***Learning Gain[1] M (SD)***	**Comparison of pre-test between the groups** Mann-Whitney U	**Comparison of post-test scores between the two groups** Mann-Whitney U	**Comparison of learning gains between the two groups[2]** Mann-Whitney U
Overall (22)	58 (12)	83 (10)	25 (14)	53 (17)	64 (18)	12 (18)	136.0	204.0***	170
Science concepts									
KMT (10)	48 (19)	78 (14)	30 (18)	50 (21)	60 (21)	10 (19)	109.0	181.5*	193.5*
Diffusion (4)	45 (20)	80 (16)	35 (17)	53 (32)	47 (39)	-6 (31)	106.0	175.5*	209.0**
Density (3)	47 (28)	77 (16)	30 (25)	56 (35)	72 (25)	17 (41)	100.0	126.5	158.5
Gas laws (9)	68 (13)	85 (7)	17 (17)	55 (19)	72 (20)	18 (25)	172.0	174.0*	128.5
Systems components									
Micro-level (7)	49 (22)	87 (16)	39 (22)	43 (22)	58 (24)	15 (18)	135.0	202.0**	192.0*
Macro-level (7)	70 (8)	93 (14)	23 (17)	57 (21)	64 (21)	7 (29)	165.0	213.0***	174.5*
Emergence (8)	56 (17)	70 (9)	14 (18)	57 (21)	70 (20)	13 (26)	112.5	107.0	117.0

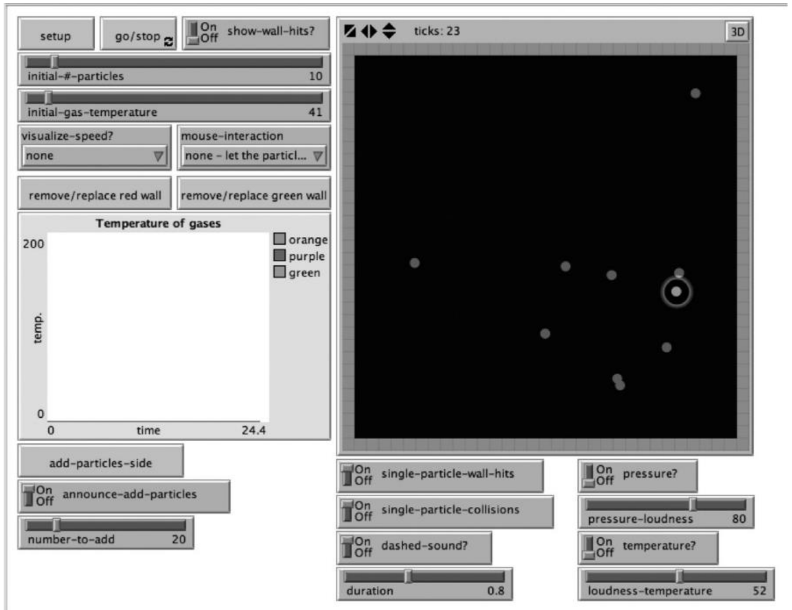
Statistical analyses were conducted using Mann-Whitney U test due to the small sample size of the groups.

[1] Learning gains were calculated for each student as *Learning Gain = (post score – pre score)*

[2] Comparison of the learning gains calculated for each student

Statistical significant indicated by: * - $p<0.05$; ** - $p<0.01$; *** - $p<0.001$

Figures



initial-#-particles 10

initial-gas-temperature 41

visualize-speed? none

mouse-interaction none - let the particl...

number-to-add 20

duration 0.8

pressure-loudness 80

loudness-temperature 52

Figure 1. Screenshot of an L2C model of gas particles in a container.

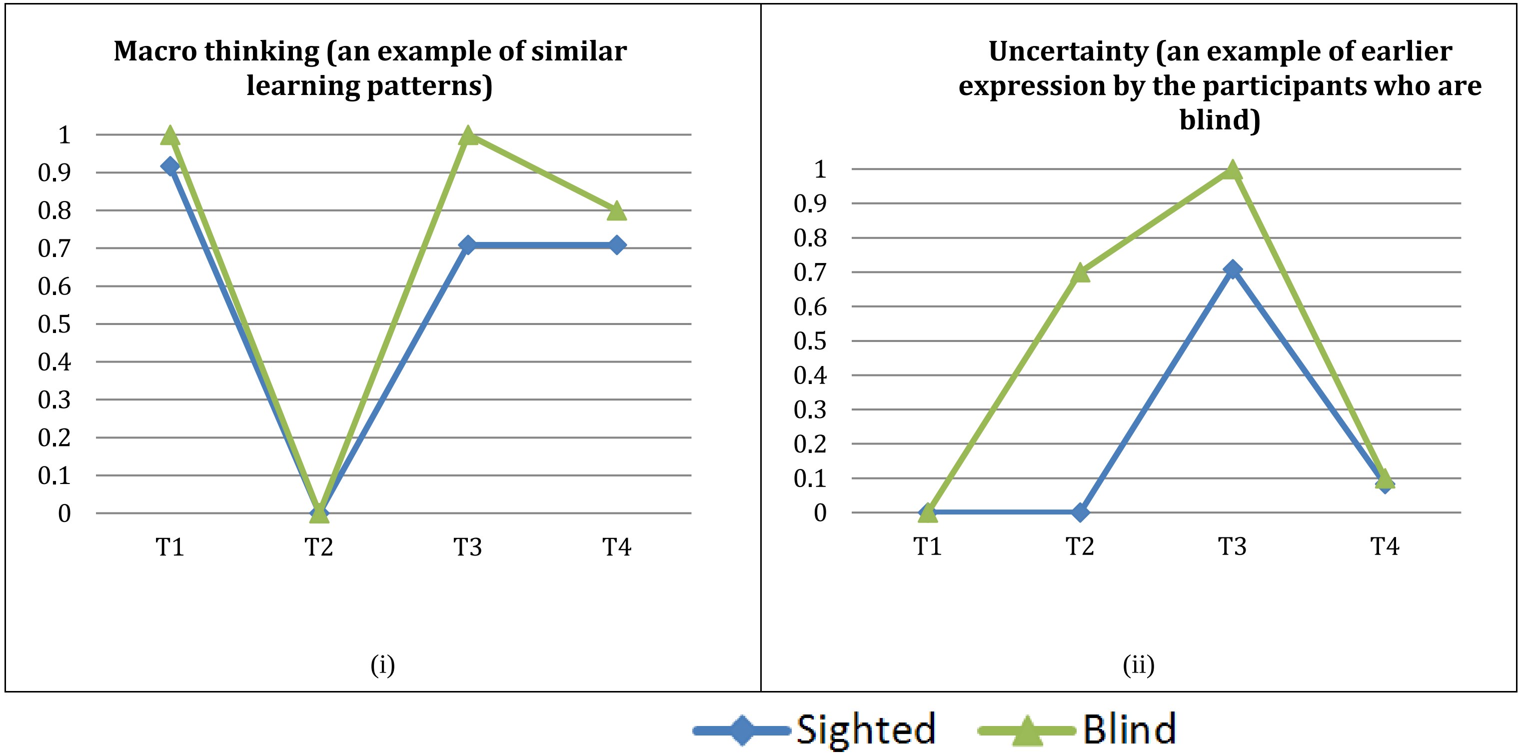


Figure 2. Learning progression of components of systems thinking.

Expression of nine components of systems thinking in items chosen in four progression analysis windows (T1, T2, T3, T4) were represented in graphs. These showed one of two themes: (i) similar learning pattern between the two groups (micro thinking, macro thinking, slippage, dynamic equilibrium and emergence), (ii) evidence that the participants who are blind provided explanations earlier in the learning process (agents' interactions, uncertainty, dynamic equilibrium and decentralized control). For brevity, only one of each theme is shown in the figure. Figure S1 showing the graphs of all nine components can be found in the supplementary materials.

The y-axis show the rate of expression of the component in the items. If the component was expressed in all items in the window, the score shown on the graph would be 1.

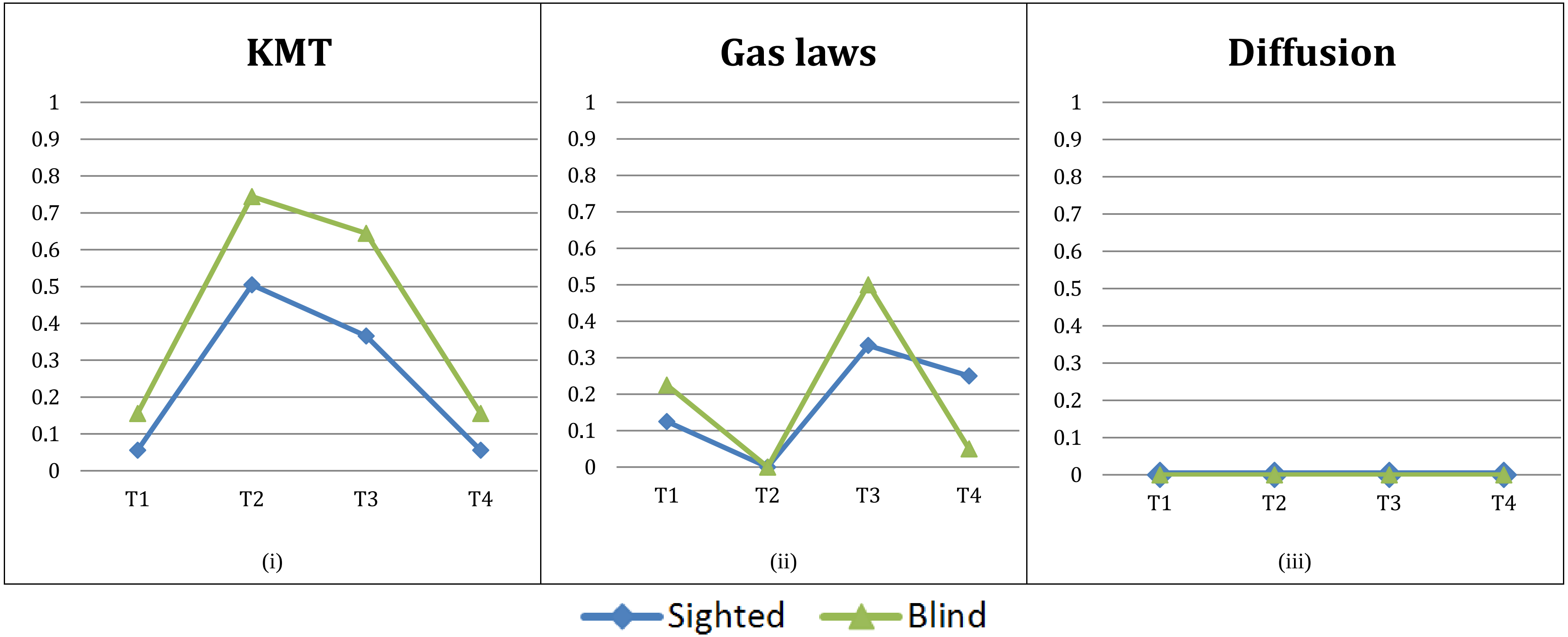
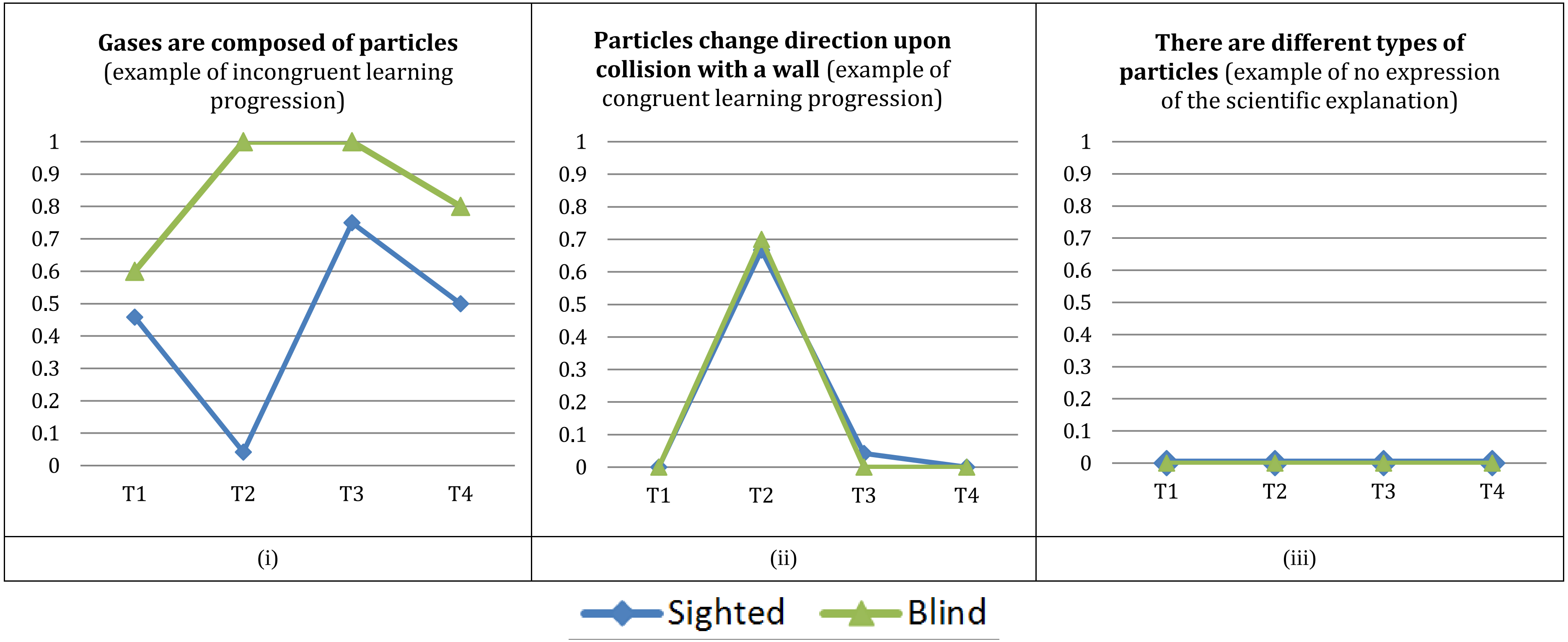


Figure 3. The learning progression of the three scientific concepts in four time windows (T1, T2, T3, T4) in the workbook.

The graphs show expression of three scientific concepts in four progression analysis windows (T1, T2, T3, T4). The y-axis show the rate of expression of the scientific concept in the items. If the concept was expressed in all items in the window, the score shown on the graph would be 1.



(i) (ii) (iii)

Figure 4. Learning progression of specific scientific explanations. The expression of twenty-six scientific explanations in four time windows (T1, T2, T3, T4) in the workbook were plotted on graphs. These graphs were categorized into one of three themes: (i) incongruent learning progressions - graphs showing big differences in the learning progressions of the two groups, (ii) congruent learning progressions - graphs that show similar learning progressions between the two groups and (iii) no expression of the scientific explanation. For brevity, only one of each theme is shown in the figure. Figure S2 showing the graphs of all twenty-six components can be found in the supplementary materials.

The y-axis show the rate of expression of the scientific explanation in the items. If the concept was expressed in all items in the window, the score shown on the graph would be 1.