Listening Versus Looking: Learning About Dynamic Complex Systems in Science Among Blind and Sighted Students

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Abstract: Listening to Complexity (L2C) is a novel sonified representation of complex systems that addresses the lack of exploratory materials in science for students who are blind. It complements agent-based models of systems by representing a micro-level individual's properties, events and location, together with macro-level variables of the system. The study examines whether this perceptual compensation creates a comparable learning environment. Students who are blind worked with auditory models; sighted students used visual models. Conceptual understanding and systems reasoning were assessed with pre- and post-test questionnaires. Learning processes were captured by analyzing their workbook writings. The L2C environment not only supported blind students' learning similarly, but also furthered their learning with one of the more challenging concepts, diffusion. Some concepts relating to the micro-level were learned earlier among the blind students. It seems that auditory representation increases sensitivity to the micro-level interactions in a way less accessible in visual representations.

Keywords: model-based learning, complex systems, science education, special education, sonification

Problem statement

How can we support students who are blind in gaining access to exploratory learning materials in science? Blind students have been integrated into public schools for decades. However, since most learning materials in science classes are based on visual information, they are often excluded from full participation (Beck-Winchatz & Riccobono, 2008). Several manuals have been written on how to teach science to students who are blind and visually impaired (Kumar et al., 2001; Willoughby & Duffy, 1989). Few learning environments based on assistive technologies have been created to support science learning and research regarding such technologies is sparse (Farrell et al., 2001, 2008; Wies et al., 2000; Zaborowski, 2006).

Addressing the problem: Listening to complexity (L2C)

Listening to Complexity (L2C) addresses a central need among people who are blind: providing equal access to the science classroom, allowing them to interact with exploratory materials, independently collect data, adapt and control their learning process. Its design is based on the assumption that the supply of appropriate information through compensatory sensory channels may contribute to science learning among blind students (Passini & Proulx, 1988). L2C is a representational form designed to overcome the lack of visual information, by providing dynamic auditory feedback to models of complex systems. Sonification, the use of non-speech audio to convey information (Kramer, 1994), is used to represent micro-level individuals, their properties and related events in space (via stereo), and macro-level descriptors of the system. Over the years, several auditory technologies have been developed for blind people (e.g. vOICe, Meijer, 1992; Lahav et al., 2008). The L2C models enables users to interact with dynamic objects that are computed in real time, providing a heightened sense of reality while learning about complex scientific phenomena. It is unique with respect to state-of-the-art learning technologies for blind people, in its sonified representation of *dynamic complex* systems, providing access to quickly changing information of both the micro- and macro-levels in a system. Important to future dissemination, it is a low-cost technology based on the robust and continually developing free NetLogo platform (Wilensky, 1999).

In this project, we addressed the learning of Kinetic Molecular Theory and the Gas Laws in middle-school chemistry, topics fundamental to the understanding of many advanced concepts in the physical sciences (NGSS, 2013). The learning environment is based on two earlier successful curricula (Levy & Wilensky, 2009ab; Samon & Levy, 2013). It consists of eight activities and includes guided exploration of agent-based NetLogo computer models, laboratory demonstrations and class discussions. The models represent a gas in a container in the form of particles (points) located within a rectangle (representing a vessel). The first models introduce students to the concept of a scientific model and to the use of NetLogo. With each additional model students explore new concepts, relationships and phenomena, which allows them to discover a different characteristic of the nature of gases. A workbook for the use of the students accompanies the unit. For most of the unit, students can progress at their own rate with the workbook that provides guiding information and questions.

The models were adapted for blind students by sonifying events and properties of a single particle such as collisions and speed, as well as global variables such as pressure. It is important to note that the information provided in the visual model is not identical that delivered in the auditory model. Individual events and properties are highlighted to a greater extent in the auditory mode. Global information such as spatial patterns of multiple individuals is provided in the visual but not the auditory model. Finally, in the auditory mode, information is provided in real time, but cannot be accessed later, as in a visual graph. The curriculum was available to the participants as text-to-speech files and in Braille. Figures were presented as tactile images.

In previous studies (Levy & Lahav, 2011) we had investigated the viability of such an approach with one model and one activity with a small sample of blind adults and found learning gains for some but not all science and systems concepts. Later studies (Lahav et al., 2014) have investigated various properties of sound that would optimally convey the most information in a way convivial for our target audience. In the present study, we examine whether such perceptual compensation creates a comparable learning environment for blind and sighted students. We compare learning outcomes and processes for a set of curricular materials in an auditory mode among blind students and in a visual model among sighted students. The research expands knowledge about how the auditory channel may compensate and complement for the visual channel among blind individuals for learning complex systems.

Theoretical perspectives

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 submicroscopic level, an experienced macroscopic level and symbolic representations (Johnstone, 1993). Research has shown that students often lack deep understanding of all three modes and often fail to coordinate between them (Novick & Nussbaum, 1981; Gilbert & Boulter, 2000).

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 modeled 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). This research aligns with the recently published US framework for science education (NGSS, 2013) that underscores system models as one of the central crosscutting concepts. A complex systems approach to teaching chemistry has been shown to help students overcome these obstacles (Levy & Wilensky, 2009ab; Holbert & Wilensky, 2014). 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 (agents) of the system.

We assess both conceptual learning in science and reasoning about complex systems among sighted and blind students 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 models for blind students compare with such learning through a visual feedback model for sighted pupils?

Methodological approach

To investigate the comparative learning of blind and sighted students a two-group pre-test-intervention-post-test quasi-experimental design was used. The process of learning is examined through analyses of the students' writings during four periods interspersed throughout the activity span.

Participants

The experimental group consisted of ten students, who are totally blind with no additional impairments (cognitive, auditory), their ages ranging 17-33, high school and university students, as well as two teachers. They all had experience in using computers and had studied science in junior- and high-school. The comparison group consisted of 31 seventh grade sighted students who attend a school serving a high socioeconomic population. Students were distributed approximately evenly between genders. Seven students' data was excluded (completed less that 18/24 questionnaire items, workbook was largely empty). The differences between the two groups results from the scarcity of individuals who are blind and recruitment issues.

Data sources

Data collected included students' responses to pre-post questionnaires and workbook items.

The questionnaires included three open items and 22 closed items, and were developed to align with the curriculum. To do so, the items in the workbook were coded for scientific content, systems thinking and reasoning types (declarative, procedural, schematic or strategic, Shavelson et al., 2003). Questionnaire items were designed in similar proportions. Most items were validated and used in previous research (Levy & Wilensky, 2009b; Samon & Levy, 2013) and printed in four differently-ordered versions.

The workbooks included 229 items, out of which four groups of items were selected as windows for analyzing students' ideas as they change throughout the learning process.

Procedure

Blind students worked and were observed individually. Each session lasted 60 minutes, and the research consisted of ten sessions that were distributed over 5-8 weeks.

Sighted students worked in their school's computer lab, 1-2 students to a computer, during four double-periods over two weeks. Each student had a workbook. The teacher and researchers conducted relatively few conversations, mainly to support students' understanding of the workbook instructions.

Both groups completed identical pre- and post-test questionnaires. Data collection was conducted differently for the two groups. While blind students worked individually with a researcher, sighted students worked individually or in pairs within a classroom setting. The choice results from the study's main goal to compare the blind students' learning with learning in normal school settings, and the scarcity of blind individuals.

Analysis schemes

Overall learning gains: An overall score for each pre- and post-questionnaire was calculated by awarding 1 point for each correct answer. From this data overall scores for each student were calculated. The aggregated scores for sighted and blind students were compared.

Learning of specific scientific concepts and systems reasoning: Questionnaire items were grouped according to the scientific concepts and central systems ideas. Scores were computed for individual students and were then aggregated and compared. In terms of scientific concepts, students' answers were coded for 26 concepts and principles that relate to the particulate nature of gas, various particle interactions and behaviors, macroscopic properties such as pressure and temperature, relations between these properties as seen in the Gas Laws and processes, such as diffusion. With respect to systems reasoning, the answers were coded for ideas regarding levels (micro, macro), emergence, interactions among micro-level entities, control, randomness and dynamic equilibrium.

Learning process: In-depth analysis of four groups of items or 'windows' in the workbook provided information about the learning process. Answers were analyzed according to a coding scheme for both scientific content as well as systems reasoning as described above for the science concepts and systems reasoning in the questionnaires.

Validity

The construct and criterion validity was determined by having five experienced science teachers and two science education experts the content knowledge questionnaires. All confirmed that the test items were appropriate for examining the issues studied in the two learning environments. Coding was checked by the researchers and by an external expert in science education. Agreement was high and disagreements were resolved uniformly by discussion.

Findings

Overall learning gains

Group scores rose significantly from pre- to post-tests (Table 3). Blind students started out with a similar score to that of the sighted students, but their post-test score is significantly higher (Mann-Whitney $U=36.0$, $p<.01$). Learning gains are comparable, though insignificantly higher for the blind students.

Science conceptual learning and systems reasoning

With respect to conceptual learning in science, the sighted students mainly learned the Gas Laws, KMT and density to a certain degree and regressed with respect to understanding diffusion. Blind students' learning gains were higher than those of sighted students. Quite distinct from the sighted students, their largest learning gain relates to diffusion. Distinct from the sighted students the Gas Laws showed least improvement, this, however, may be a ceiling effect, as the score in the post-test is 85%. Regarding systems reasoning, the groups are similar in the pre-test and in the post-test.

Learning processes

Processes of learning along the four windows for both groups are presented in Appendix A. Comparing these temporal curves shows that for most concepts, the shapes of the curves are similar for the two groups. This is not true for including interactions, uncertainty and decentralized control, where the blind students provided more such explanations earlier in the learning process. Another result from the comparison is the higher proportion of students expressing each of the concepts (systems, science) among the blind group with respect to the sighted group.

Table 3: Pre-test and Post-test Scores (%) and Learning Gain Comparisons for the Blind and Sighted Students, Overall, by Concept

	Blind Students		**Sighted Students**		**Learning Gain Comparison**
Learning Concepts (# of items)	***Pre-test M (SD)***	***Post-test M (SD)***	***Pre-test M (SD)***	***Post-test M (SD)***	***Mann-Whitney U***
Overall (22)	58 (12)	83 (10)	53 (17)	64 (18)	90.0
Science concepts					
KMT (10)	48 (19)	78 (14)	50 (21)	60 (21)	177*
Diffusion (4)	45 (20)	80 (16)	53 (32)	47 (39)	145**
Density (3)	47 (28)	77 (16)	56 (35)	72 (25)	138
Gas laws (9)	68 (13)	85 (7)	55 (19)	72 (20)	112
Systems thinking					
Micro-level (7)	49 (22)	87 (16)	43 (22)	58 (24)	158
Macro-level (7)	70 (8)	93 (14)	57 (21)	64 (21)	160
Emergence (8)	56 (17)	70 (9)	57 (21)	70 (20)	107

Conclusions and implications

The study compared blind students' use of auditory computer models to sighted students use of visual models. With respect to sighted students, the auditory representation not only supported blind students' learning similarly, but was even related to greater learning of diffusion, a challenging concept. In analyzing the progressions we can see that the individual science and systems concepts were learned at similar times, corresponding to the learning materials. However, regarding two central systems concepts: interactions between individuals and uncertainty, the blind students learned and applied these concepts earlier.

Earlier, we have compared the visual and auditory models, noting the greater salience of micro-level individuals. The L2C's auditory representation seems to have increased sensitivity to micro-level interactions (e.g. colliding) in a way that is less accessible in visual representations. We had chosen to sonify particular events for one particle and time progressions of global variables such as pressure. In fact, much information in the visual array is missing in the auditory array: many other particles, each moving about, colliding and bouncing off walls. It would seem that this filtering of information helps students focus on these very interactions that are subtle in an array of many particles, and notice their random changes over time, evidence from which uncertainty can be derived.

Limitations to this study include the different character and treatments of the two groups: the experimental group included young adults, who interacted one-on-one with a researcher, while the comparison group included middle-school students who worked in pairs within a classroom. Such limitations were inevitable due to a limited sized blind population.

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. It also raises questions for further research into the use of auditory representations to facilitate learning among sighted learners.

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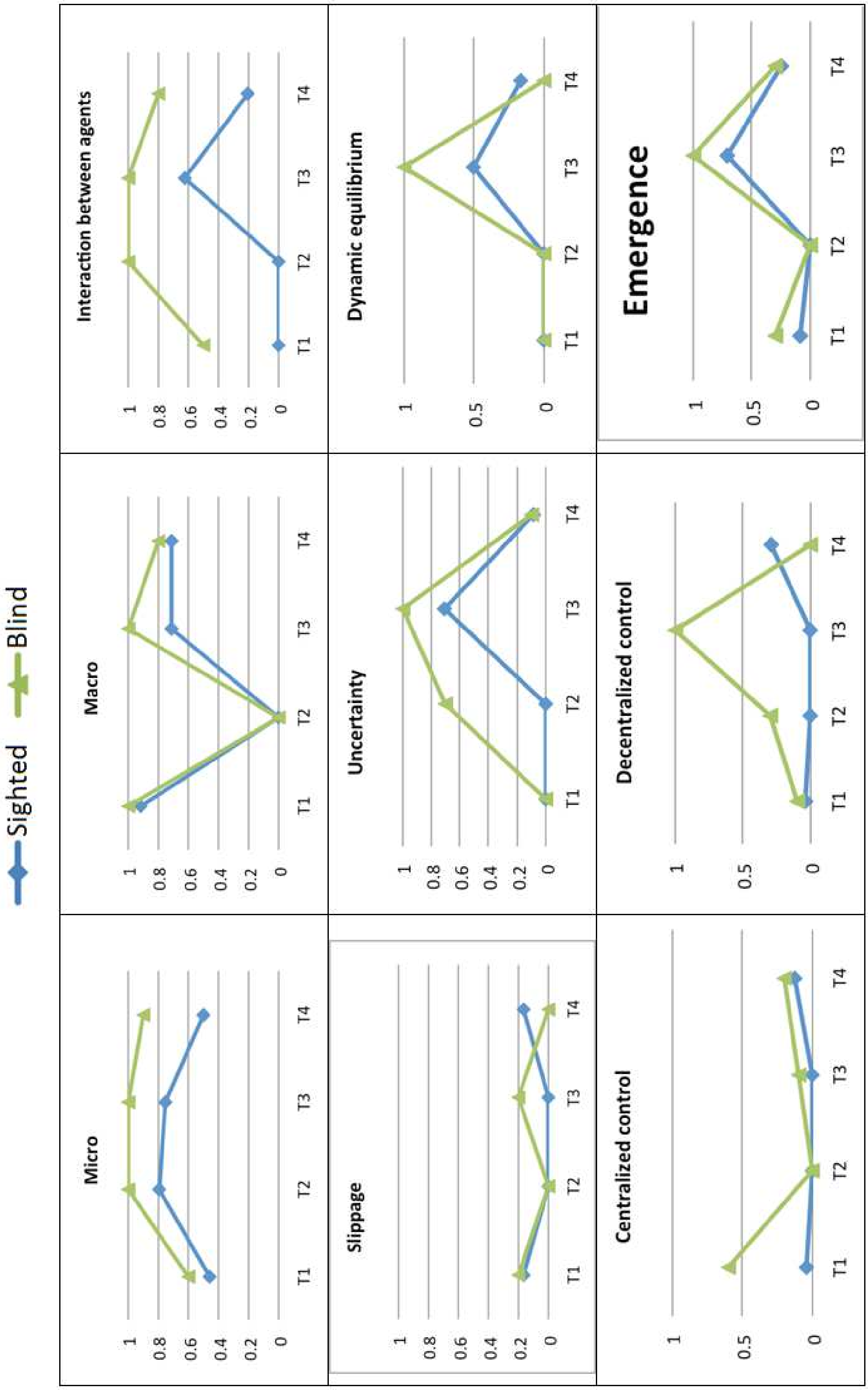
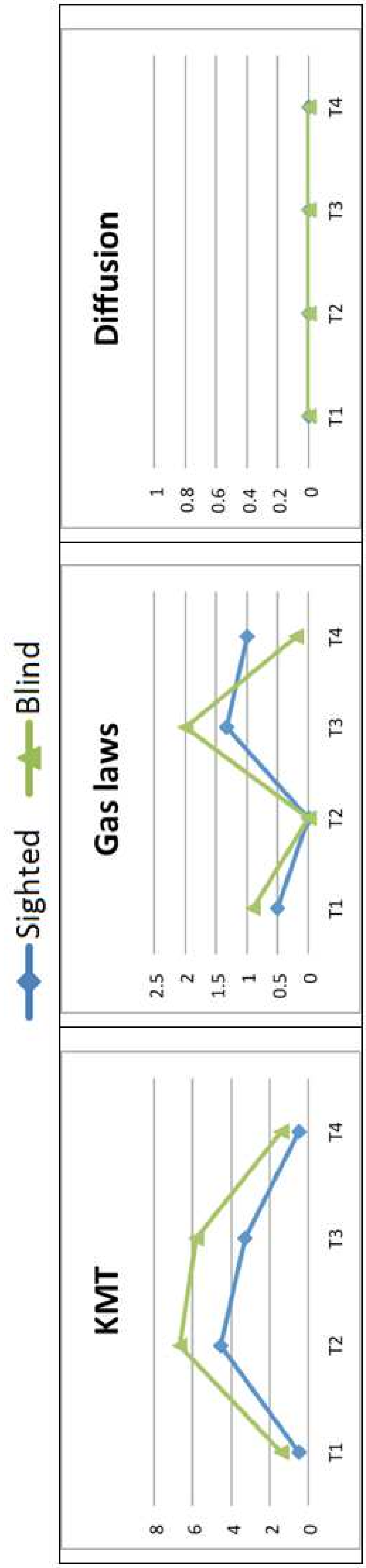
Appendix A: Learning Progressions for Systems Reasoning and Conceptual Learning in Workbook Activity Windows





Sighted
Blind
KMT
Gas laws
Diffusion
8
6
4
2
0
2.5
2
1.5
1
0.5
0
1
0.8
0.6
0.4
0.2
0
T1
T2
T3
T4