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Examining the use of adaptive technologies to increase the hands-on participation of students with blindness or low vision in secondary-school chemistry and physics

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To determine whether a suite of audible adaptive technologies would increase the hands-on participation of high school students with blindness or low vision in chemistry and physics courses, data were examined from a multi-year field study conducted with students in mainstream classrooms at secondary schools across the United States. The students worked with sighted laboratory partners. Four categories of data were analyzed with regard to levels of hands-on participation, including quantitative coding of video-recorded laboratory lessons, qualitative assessment of the same videos, student interviews, and teacher interviews. Evidence in support of the efficacy of the technologies to increase the students' hands-on participation during laboratory lessons was substantial. However, certain factors affected the quantitative interpretation of the data: students with usable low vision experienced similar levels of participation both with and without the adaptations, and students with little usable vision often required more time than did students with full vision to accomplish some laboratory tasks. Additional factors inherent to natural educational environments were also determined to have strong effects on student outcomes.

Relatively few students with blindness or low vision (BLV) pursue advanced studies in the sciences and enter careers in the science, technology, engineering, and mathematics (STEM) fields. While students with BLV in mainstream science courses traditionally depend on others to conduct most lab activities and report observations (Miner *et al.*, 2001; Pence *et al.*, 2003), many find this approach frustrating—and worse, uninspiring (Dewey, 1938; Piaget, 1970; Supalo, 2010)—leaving them uninterested in further scientific pursuits (French, 1924; Rutherford and Ahlgren, 1990; Paris *et al.*, 1998; McPhail *et al.*, 2000; Pence *et al.*, 2003). This may help explain why so few persons with BLV are in the professional scientific community, the low numbers of which are noted or implied in various sources (Division of Science Resources Statistics, 2003; Scadden, 2005; Allum, 2010). Further, active participation in planning and carrying out investigations is one of a number of essential epistemic practices identified as essential to science teaching and learning in recent recommendations by the National Research Council (National Research Council, 2012).

Students with BLV in mainstream chemistry and physics classrooms generally depend on laboratory partners or personal laboratory assistants to conduct activities and report visual observations. While this methodology has been educationally successful for some (Miner *et al.*, 2001), a focus on increased physical involvement and independence may be a preferable approach (Supalo, 2010). Many educators and researchers, including Piaget (Piaget, 1970) and Dewey (Dewey, 1938), have long posited that active physical participation in science experimentation is highly beneficial to the educational experience (French, 1924; Scadden, 2005), including for students with blindness and other disabilities (French, 1924; Burke, 1932; Long, 1940; Bryan, 1952; Bryan, 1957; Long, 1973; Linn and Thier, 1975; DeLucchi and Malone, 1982; Lynch *et al.*, 2007; Winograd and Rankel, 2007). In recent years, numerous papers on classroom adaptations, technologies, and activities with the potential of increasing the physical hands-on involvement for science students with BLV have been published (Neppel *et al.*, 2005; Penrod *et al.*, 2005; Supalo, 2005; Bromfield-Lee and Oliver-Hoyo, 2007; Neely, 2007; Bromfield-Lee and Oliver-Hoyo, 2009; Pereira *et al.*, 2011; Bonifácio, 2012; Boyd-Kimball, 2012; Wedler *et al.*, 2012; Garrido-Escudero, 2013; Harshman *et al.*, 2013; Pereira *et al.*, 2013; Supalo *et al.*, 2014; Supalo and

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Kennedy, 2014; Wedler *et al.*, 2014). The National Science Foundation funded a three-year grant titled Independent Laboratory Access for the Blind (ILAB) that contributed to this body of educational research (Supalo, 2007). This project was a mixed-methods investigation of the efficacy of ILAB-developed adaptive technologies to increase the hands-on participation of secondary-school students with BLV enrolled in mainstream chemistry and physics courses.

These technologies included talking tools, as well as audible interfaces to commercially available tools. The results of Year 1 of the three-year study have already been reported (Supalo, 2010). The present article examines the extent of hands-on participation of students during Years 2 and 3, for which the approach of the study was refined.

By developing and providing a range of audible adaptive technologies, we sought to empower students with BLV to independently perform data-collection activities alongside their lab group partners during laboratory lessons. In this paper, we explore the following research question: would the use of such technologies foster more hands-on, multisensory participation by students with BLV as members of lab groups with sighted students in laboratory classroom environments?

Key predictions were: (1) when students with BLV use the adapted technologies during laboratory lessons, they will achieve a more hands-on science experience than when they do not use the technologies during laboratory lessons; and (2) when students with BLV use the adapted technologies during laboratory lessons to achieve a more hands-on science experience, they will more fully participate in the activities of the lab group as compared to laboratory lessons when they do not use the technologies.

For the purposes of the study, the term ''hands-on'' was broadly defined as involving direct physical action with the goal of obtaining data through any of the available senses, often—but not necessarily—including the use of adaptive tools.

Results for Year 1 were substantially positive (Supalo, 2010). For the two subsequent years of the study, the hypotheses and data analysis methodologies were somewhat refined. In an investigation of the data from Year 2 and Year 3 for the revised Hypotheses #1 and #2 (listed above)—both concerning the students' hands-on participation in laboratory activities—use of the adapted technologies during labs was shown to increase participants' hands-on performance as compared to labs when the technologies were not used (Scadden, 2005).

The present article concerns the remaining hypotheses, which are centered on effects potentially resulting from this increased physical participation in a further exploration of the data from Years 2 and 3:

When students with BLV use the adapted technologies during laboratory lessons to achieve a more hands-on science learning experience:

H3: *They contribute more productively to discussions in their lab groups than during laboratory lessons when they do not use the technologies.*

H4: *Their social acceptance into their lab groups is greater than during laboratory lessons when they do not use the technologies.*

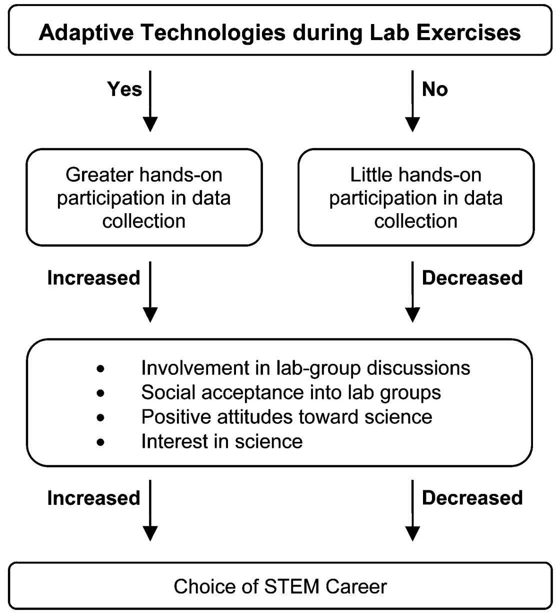

Fig. 1 How the use or non-use of the adaptive technologies during laboratory lessons was expected to impact the lab-group inclusion and STEM interest of students with BLV. (Adapted from Supalo (Supalo, 2010).)

H5: *Their attitudes toward science are impacted positively.*

H6: *Their interest in science is impacted positively.*

H7: *Their interest in pursuing STEM career paths is impacted positively.*

As illustrated in Fig. 1, these hypotheses are based on the premise that direct, hands-on experiences in science laboratory courses may be more advantageous in several aspects for students with BLV than is the traditional methodology of relying on others (Linn and Their, 1975; DeLucchi and Malone, 1982; Winograd and Rankel, 2007; Supalo, 2010).

Experimental overview

Testing of hypotheses #1–7 was conducted under the same Institutional Review Board consents, and involved the same students, laboratory lessons, interviews, data instruments, and data analysis. Field-testing was conducted in natural classroom settings with the participants working in lab groups having one to five sighted partners.

The sources of data included audiovisual recordings of laboratory lessons, student interviews conducted both before and after the school term, and post-course interviews with the teachers. Many audiovisual recordings of lessons received by the researchers were not utilized for a variety of reasons, including poor quality and not adhering to the defined parameters. This resulted in some students having only a few usable videos, while others had many more. From among the usable videos, a sample set was chosen.

The videos were analyzed for pertinent behavioral qualities of the students with BLV and their partners, with accuracy being checked during repeat viewings. The properties listed in Box 1 were the foundation for video analysis, but other characteristics or conditions of potential interest were likewise chronicled. Additionally noted for each video were the number and gender of the lab partners, and whether or not they appeared in other lessons.

Box 1: Properties examined during qualitative analysis of the audiovisual recordings of the laboratory lessons described in Appendix 1.

- The overall hands-on performance of the student with BLV.
- Whether the student seemed comfortable using the adapted technologies.
- Whether the student used the adapted technologies correctly and efficiently.
- The student's apparent level of understanding of the lesson material.
- Which lab-group member(s) assumed leadership.
- Whether the student and the partners seemed comfortable with each other.
- How intellectually involved the student was in the lab group discussions.
- How accepted the student seemed to be within the lab group.

Pertinent sections of audio-recorded interviews were transcribed verbatim and analyzed. The students' pre-course interview responses were compared with their post-course responses, and responses from each student were compared to those of the other students. The teachers' post-course interview responses were compared with the students' responses, and responses from each teacher were compared to those of the other teachers. All responses were compared to the video data and to the hypotheses.

Participants and settings

The sample population of students with BLV was comprised of two females and four males from six schools in the United States, a single participant per school, with some diversity in race, geographic location, and community demographics. Two students had some usable vision; the other four were either completely blind or very nearly so. All attended mainstream secondary institutions. Signed consent forms were obtained from students, parents, and teachers, as required by the Institutional Review Board (case #24587) of The Pennsylvania State University.

Each student participated in field testing at his/her own school in natural classroom settings. Three of the students were enrolled in chemistry courses, and three were enrolled in physics.

The students and their teachers were provided with training in using the adapted technologies prior to the beginning of their respective courses. The technologies were incorporated into the laboratory components of participants' respective science courses during some lessons but not during others, so the control and experimental conditions could be compared. Only lab lessons in which the participants worked in lab groups (with sighted students) were included in analysis, so the hands-on performance of the participants could be compared with that of their partners. None of the students with BLV had personal laboratory assistants in the labs that were analyzed.

Technological intervention

The technologies developed for the study primarily included electronic devices and software adaptations, which produced either audible tones or spoken numerical values. The cornerstone of this work was a software interface between the Vernier Software & Technology line of classroom laboratory probeware and the Job Access with Speech (JAWS) screen-reader software (Supalo *et al.*, 2007; Supalo *et al.*, 2009a, 2009b; Supalo, 2010). JAWS, a commercial text-to-speech product available from Freedom Scientific and widely used by persons with BLV, transforms compatible screen displays of text into speech.

The software interface, linking JAWS with Vernier's Logger Pro data-collection software in conjunction with Vernier probeware and LabPro data-collection instruments, enabled the data gathered through Vernier LabPro devices to be transformed into audible announcements *via* computer (Supalo, 2007). This adaptation made the entire range of Vernier probeware readily accessible to persons with BLV. One such setup is seen in Fig. 1. Ohaus balances, which can interface with Vernier equipment through USB ports, were similarly made audible (Fig. 2).

Complementing the software interface, hardware custom-designed for this study included the Submersible Audible Light Sensor (SALS) (Supalo *et al.*, 2006; Supalo *et al.*, 2008; Supalo *et al.*, 2009a, 2009b; Supalo, 2010) and Color Analysis Laboratory Sensor (CALS) (Supalo, 2010), developed in the Research

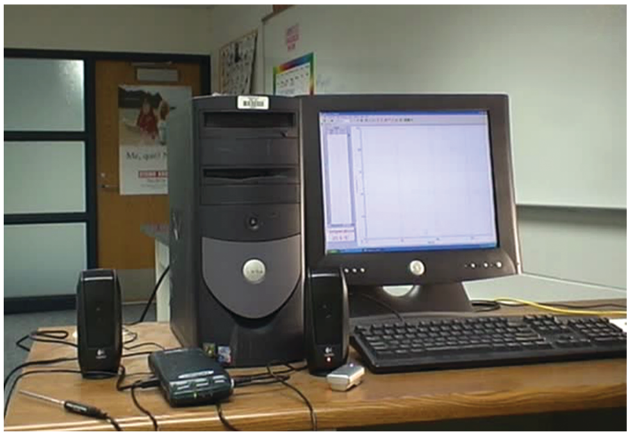

Fig. 2 In an image captured from one of the videos, a computer is linked to a LabPro control box and probe. Data displayed on the computer monitor is navigable *via* JAWS.

Instruments Facility in the Chemistry Department at The Pennsylvania State University. The SALS detected whether a liquid was light-transmissive or opaque and emitted either spoken frequencies or audible tones. The CALS spoke the colors of solids, liquids in test tubes, or liquids in beakers, depending on which of three specialized probes were used with the control box. The two CALS probes for liquids were not submersible and were designed to take readings of the colors of liquids through glass.

Data collection

A large body of data was gathered in the form of audiovisual recordings of laboratory lessons, audio recordings of pre-/post-course student interviews, and audio recordings of post-course teacher interviews. Multiple sources of evidence were examined to provide a layered picture of the conditions and events that occurred during the study (Wolcott, 2001; Maxwell, 2005). A mixed-methods approach was used because neither quantitative nor qualitative analysis alone would have been sufficient to address the complexities of the research question (Creswell, 2009).

Video data

Of the lessons that were adaptable with the technologies, a randomized assignment process determined which incorporated the technologies and which did not. For each participant, a mix of both types of lessons as usable video recordings was required.

Labs involving the adapted technologies were labeled I-lessons; those not involving these technologies were N-lessons. A ''lesson'' was defined as a discrete educational unit within the course materials, focusing on one concept or a closely related set of concepts and having a beginning, middle, and end. While most lessons took up all or a majority of one class period each, some lessons occupied less than a class period, and some required more than one class period.

One video camera at each school was used by the teacher to record the participant and his/her lab groups in action. In most cases, the teacher set up the camera in a static location for the duration of a lab, occasionally adjusting the position as needed. The recordings were burned onto mini-DVD discs, which were mailed to us. Some teachers provided large numbers of audiovisual recordings, while some sent only a few.

Not all audiovisual recordings that were received were included in analysis. For participants who had many recordings, a sample was chosen. For those having a small number, the selections were limited. Lessons were omitted from the study for a variety of reasons, such as the camera angle inadequately revealing the activities of the participant and/or the lab group partners, or showing labs not involving group partners at all (the participants worked either alone or with the teacher or teacher's aide).

Interview data

Interviews from scripted sets of questions were conducted pre- and post-course with each participant and post-course with each teacher. Questions included those related to students' career plans, previous experiences in science classes, interests in and attitudes toward science, various aspects of laboratory participation, and the adapted technologies (Supalo, 2010). Numerous unscripted questions were also asked to solicit additional information depending on the answers to scripted questions. The interviews were conducted by the first author, a chemist who is blind. Interviews were audio-recorded, and all substantive discussion was transcribed for analysis (Supalo, 2010).

Data analysis

Of the 54 video-recorded lessons that were received for the students in the study, 27 were analyzed: 12 cumulative for the three schools in Year 2, and 15 cumulative for the three schools in Year 3. Thirteen were N-lessons and 14 were I-lessons. The numbers of N-lessons and I-lessons were not evenly distributed among the schools, due to the varying numbers of videos received per school and the challenges in selecting usable videos.

For the quantitative data, the activities of the participant and his/her lab group partners were coded for each of the selected video-recorded lessons. Only activities determined to be ''laboratory-goal-directed actions,'' or LGDA, were included in the coding as described in Appendix 2. While lab discussion and setup—as interactive activities that engage students—are known to contribute to student learning, these activities were not included in the video coding and analysis because they did not involve the taking of data with the adaptive technologies. The adapted technologies were designed for taking data, so LGDA was defined as those actions that were approximately directed toward data collection, and thus did not include setup, cleanup, reading experimental procedures, discussing, waiting, making calculations, taking notes, or listening to the teacher.

A ''targeted transcript'' was constructed for each video analyzed, briefly describing every instance of LGDA, and indicating the beginning and ending time of each. The durations of the instances of LGDA were calculated. For each lesson, the total number of seconds of LGDA was determined for the student with BLV, individual lab group partners, and the group as a whole. From this, the percent of time engaged (PTE) for each person in the lab group was calculated, revealing the percentage of the total LGDA time attributable to specific lab group members.

Because the number of lab group partners varied from one to five in the lessons analyzed, PTEs from one lab were often not directly comparable to PTEs from other labs. For instance, a participant's PTE of 20% for a lesson would be interpreted quite differently if the student had one partner or five. Consequently, to produce an index of participation controlling for the variation in the number of lab partners across lessons, all PTEs were converted into parity-weighted percentages. This was accomplished by multiplying each person's PTE by the number of people in the lab group. For example, a participant's PTE of 20% for a group with one partner would be $20 \times 2 = 40\%$ parity weighted, meaning that the participant contributed only 40%

of parity, while the partner contributed 160%. Conversely, parity in a lab group containing the participant and five partners would be 100/6 = 16.7%, and a PTE of 20% would become 20 × 6 = 120% parity weighted, revealing that the participant contributed 120% of parity regarding LGDA time. Values greater than 100% meant that a participant contributed more than his/her equal share of time on LGDA.

The videos were also qualitatively analyzed regarding the hands-on performance of the students with BLV as compared to their lab partners. Among the features examined were how the qualitative aspects of their performance compared to their parity values, whether they used the adapted technologies correctly and efficiently, how well the two partially sighted students seemed to see in laboratory environments, and how the performance of the students with partial vision compared to that of the students who were fully blind or nearly so.

For the audio interviews with students and teachers, all transcripts were double-checked for accuracy, and the content of statements qualitatively analyzed for results. Pre- and post-course statements were compared, as were student and teacher statements.

Results

Multiple streams of data—videos, student interviews, and teacher interviews—were used for triangulation of results.

For the quantitative analysis of the videos, the data were transcribed and encoded using a common set of rules, which was allowed to become more detailed with time (Skoog and West, 1982). Overall consistency in coding was achieved by rechecking the set of transcripts near the end of data analysis and making adjustments as necessary to ensure that all criteria were followed. Minor inconsistencies—such as whether or not a few brief glances from a lab partner at a chemical solution were coded as LGDA—were often ignored if adjustment would have produced only trivial changes in parity-weighted percentages.

Because all analyses (except the *t*-tests) were done by one researcher, two video-recorded lessons—one each from Years 2 and 3—were completely reanalyzed quantitatively as additional confirmation of the reliability of the results. These repeat analyses resulted in BLV parity values very close to the originals. Quantitative and qualitative analyses of the video-recorded lessons were additionally confirmed *via* multiple viewings throughout the analysis process. The authors also conferred regularly and at length, discussing in-depth the results as they developed and reached consensus on ambiguities.

Quantitative (videos): parity-weighted values

Tables 1 and 2 summarize the findings for each student with BLV. All student names are pseudonyms. See Appendices 3 and 4 for complete information.

In Year 2, Nate's averaged parity-weighted percentage of participation across the four N-lessons (112) was the same as his I-lesson average. For Anna, the parity-weighted value for the single N-lesson (118) was somewhat higher than the average of the two I-lessons (102). The values for Will's two N-lessons were widely divergent and straddled the value for his single I-lesson. The average of all I-lessons in Year 2 (100) was similar to the N-lesson average (97).

The results for Year 3 more consistently showed a difference between the values for N-lessons and I-lessons. All three participants in Year 3 had higher averaged parity-weighted values for their I-lessons than for their N-lessons, and the average of all I-lessons together (90) was substantially higher than the N-lesson average (56).

Standard deviations for the averaged values of parity-weighted participation were calculated by pooling the data by year. For Year 2, the results for N-lessons were 97 ± 55 and I-lessons 100 ± 19; for Year 3, N-lessons were 56 ± 38 and I-lessons 90 ± 37. For both years together, overall values and standard deviations were N-lessons 78 ± 51 and I-lessons 93 ± 31.

Table 1 Summary of videos analyzed for Year 2

Participant information	N or I[a]	Lab description	# Partner(s)[b]	BLV parity-weighted %[c]
Nate[d]	N	Acceleration of gravity	1	55
Honors Physics	N	Potential energy	1	148
	N	Find work in collision	1	86
	N	Conservation of momentum	1	157
	I	Friction	1	102
	I	Pendulum	1	121
Anna	N	Identifying liquids through the senses	2	118
Chemistry in the Community	I	Determining pH of Solutions	2	115
	I	Observing food coloring in liquids	2	88
Will	N	Conservation of momentum	4	0
Honors Physics	N	Force mini-labs	2	114
	I	Electricity	1	74

[a] "N" indicates labs conducted without the adapted technologies; "I" indicates labs conducted with the technologies. [b] The number of lab group members in addition to the student with BLV. [c] A comparison to parity of the amount of time the student with BLV spent on laboratory-goal-directed actions. A value <100 is below parity; ≥ 100 indicates parity or greater. The range of error in individual data is estimated at ±5%. [d] Nate and Dale both used the adapted technologies during different courses in Year 1, which may or may not have affected their parity values listed above.

Table 2 Summary of videos analyzed for Year 3

Participant information	N or I[a]	Lab description	# Partner(s)[b]	BLV parity-weighted %[c]
Yasmin	N	Diffusion	2	2
Chemistry	N	Acid base	2	39
	I	Cations and anions	2	32
	I	MgO	3	117
	I	Percent yield	3	71
Ken	N	Classification of matter	2	61
Chemistry	N	Percent yield	2	63
	I	Discovering density	2	83
	I	Average mass	1	102
	I	Families of elements	1	135
	I	Molar volume of a gas	3	36
Dale[d]	N	Trigonometry	5	50
Physics	N	Acceleration of gravity	5	119
	I	Friction	3	120
	I	Inclined plane	5	112

[a] "N" indicates labs conducted without the adapted technologies; "I" indicates labs conducted with the technologies. [b] The number of lab group members in addition to the student with BLV. [c] A comparison to parity of the amount of time the student with BLV spent on laboratory-goal-directed actions. A value <100 is below parity; ≥100 indicates parity or greater. The range of error in individual data is estimated at ±5%. [d] Nate and Dale both used the adapted technologies during different courses in Year 1, which may or may not have affected their parity values listed above.

Standard deviations are typically used to determine random error in replicate measurements of the same quantity (Skoog and West, 1982). However, the parity-weighted values in Tables 1 and 2 contain systematic error as well as random error, arising from the fact that no two experiments or participants were alike: the students with BLV differed in personality, the teachers differed in personality and teaching approach, the lessons varied in content, the specific adaptive technologies varied from one lesson to another, and the interpersonal dynamics among lab group members were highly diverse.

Next, *t*-tests were used to determine whether the differences between the averaged parity-weighted values of the I-lessons and N-lessons were significant at a given level of confidence, and statistical significance was found in some of the data.

In the *t*-test (see eqn (1)) (Skoog and West, 1982), s is the experimentally determined standard deviation for a given data set, n_{I} and n_{N} are the numbers of I-lessons and N-lessons, respectively, and t is a statistical quantity that depends on the number of degrees of freedom and the chosen confidence limit:

$$I_{\mathrm{avg}} - N_{\mathrm{avg}} > t_s\sqrt{\frac{n_{\mathrm{I}} + n_{\mathrm{N}}}{n_{\mathrm{I}} n_{\mathrm{N}}}} \quad (1)$$

The *t*-test results are summarized in Table 3. In Year 2, when both students with partial vision were participants, the average parity-weighted value of the I-lessons was statistically minimally different from the average parity-weighted value of the N-lessons. In contrast, in Year 3, the parity-weighted average for the I-lessons was statistically greater than the parity-weighted N-lesson average at the 95% confidence level. Pooling both years together, a statistically significant difference between the I-lessons and N-lessons was found at the 85% confidence level, but not at the 95% confidence level.

Overall, this analysis supports our prediction that the students with BLV in this study (especially those who were blind or nearly so) would quantitatively experience more hands-on laboratory participation during the I-lessons than during the N-lessons.

For the chemistry lessons (predominant in Year 3), the difference between I-lessons and N-lessons was found to be significant at the 95% confidence level. Statistical significance was not found at the 95% confidence level for the physics lessons (predominant in Year 2).

Qualitative (videos): insights and revelations

The qualitative data provided a richly detailed and nuanced body of information, revealing some unexpected findings. Among them was that higher parity-weighted percentages were not necessarily entirely due to greater frequency and variety of goal-directed activities. For instance, Ken habitually worked very slowly and carefully, which biased his results toward higher parity-weighted values. In fact, the students with BLV as a group often took longer than did the sighted students to accomplish some tasks—such as manipulating laboratory apparatus, using supplies, and conducting procedures both with and without the adapted technologies—likewise inflating their parity values.

Another finding was that the two partially sighted students, both of them participants during Year 2, could actually see well enough to take many data points visually during N-lessons and I-lessons alike. For example, Anna could see the colors of solutions and pH strips, and Nate had enough visual acuity to read a meter stick to half-inch accuracy, potentially explaining why their I-lesson parity averages differed so little from their N-lesson parity averages. Nate's wide differences in individual N-lesson parity values were generally due simply to the voluntary division of tasks between him and his partner. However, this is not to minimize the fact that Nate and Anna both had substantial visual disabilities.

Table 3 Statistical analysis of pooled data

Data set	s	Degrees of freedom	Confidence level (%)	t	$I_{\mathrm{avg}} - N_{\mathrm{avg}}$	$t_s\sqrt{\frac{n_{\mathrm{I}} + n_{\mathrm{N}}}{n_{\mathrm{I}} n_{\mathrm{N}}}}$	I_{avg} significantly $> N_{\mathrm{avg}}$?
Year 2	14.7	10	95	1.81	3.1	15.6	No
Year 3	29.1	13	95	1.77	34.1	27.2	Yes
Both Years	31.7	25	95	1.71	15.6	20.9	No
Chemistry	27.5	12	95	1.78	30.0	27.3	Yes
Physics	36.9	11	95	1.80	14.7	37.8	No

Will exhibited the most unusual set of parity values, with one N-lesson at 0 and another at 114, and the single I-lesson at 74. This spread of values would have been difficult to interpret without qualitative analysis. In two of the three lessons, Will was partnered with boys who were obviously his friends. In the N-lesson for which he contributed no LGDA, he did not appear to know his partners well and took no initiative to participate. During the N-lesson with a parity value of 114, he was much more verbal and participatory, consistently engaging with his partners and the educational material. A second major reason for increased participation in this lesson was a BLV-accessible tactile protractor, which was not among the tools developed for this study. Using this protractor, Will took the lead by measuring all the angles, with the assistance of his partners.

Of all the videos analyzed for this study, Will's I-lesson on electricity may offer the most striking example of success with the adapted technologies. Using the JAWS/Logger Pro interface, Will independently took many data points—both voltmeter and ammeter values—throughout this lab. He explained to the teacher that he had audible access to Cartesian graphs and tables in addition to meter readouts. His lower parity weighting of 74 in this lesson as compared to the N-lesson with 114 reflects greatly increased efficiency due to the audible adaptation and his highly competent operation of it. During the N-lesson, he'd had to work relatively slowly to measure the angles tactilely, but in this I-lesson he was able to take data points quickly and easily. Consequently, the parity value of 74 is a positive result even when compared to the N-lesson value of 114.

Further evidence of the efficacy of the adapted technologies can be found in the qualitative analysis of the other students' lessons. All of the students used the technologies with some success. While Nate could see the computer screen to a certain degree, he accessed some of the data through the audible software interface in both of his analyzed I-lessons. Yasmin was observed using the talking balance and SALS; Ken was observed using the talking balance, SALS, and temperature probe; and Dale was observed using force meters. Additional usages of other of the adapted technologies were mentioned in some of the interviews. All of these observed and reported usages not only increased the amount of hands-on participation for the students, but also increased the range of their activities, as they would not have been able to take many of these types of data without adaptive technologies.

In the lessons analyzed, Anna had the least success with the adapted technologies. While she managed to take some data with the CALS, she did so not by inserting filled glass beakers into the beaker holder as the device was designed, but by pouring liquids directly into the beaker holder. During the pH lesson, she repeatedly attempted to take pH readings with the SALS, which does not measure pH. However, the interview evidence indicates that she improved in her understanding and usage of the technologies over time.

Qualitative (interviews): in their own words

While the lessons analyzed represented a portion of the labs for each course, the interviews covered the entire course experience for each participant. Other than mentions of a few glitches and equipment failures, interview evidence from the students and teachers was positive regarding the adapted technologies as increasing the students' hands-on participation during laboratory lessons. In their pre-course interviews, most of the students indicated that they had previously participated only in a very limited fashion during earlier group laboratory activities. The following exchange with Anna was particularly telling:

Interviewer: *At any time previous did you feel in one of these group situations that the group felt you were not contributing a lot to the group? Did you ever get that sense?*

Anna: *I don't know if the group ever felt it, but I know I've felt it. Because a lot of times if there was something so visual, a lot of times they would just do it and they wouldn't let me do anything for it, even when I would ask, even when I would ask to do something, they would not let me do it at all.*

In contrast, during her post-course interview, when asked about the specific aspect she had enjoyed the most regarding her favorite lab lesson during the study, she said:

Anna: *Being able to tell what's going on and not have people describe it for me.*

Interviewer: *So you liked to gather that on your own?*

Anna: *Yeah. I like to be independent with everything that I do.*

In her pre-course interview, Yasmin stated that her earlier participation in science labs had been mainly as her group's note-taker:

Interviewer: *If you want to elaborate for me a little more on that, how you participated in science labs in the past. Was it primarily just as the recorder? You wrote down what they told you? Not much more than that?*

Yasmin: *Not much more, though sometimes I would ask, because sometimes I would just get so bored that I would ask if I could stir something, so sometimes I would be the group's stirrer I guess. I think that was about it.*

Yasmin's teacher said to the interviewer post-course that, "I really feel like maybe during the other years, she didn't really feel like she was a part, you know, she was just kind of a bystander. Where I think because of your support I've been letting her just be such an active member, a contributing member of her group. I think that worked really well for her. And for me."

Ken had this to say during his post-course interview: "I really liked being able to participate in the labs. With the ILAB tools I felt that I was able to participate better than I would have been able to participate without them. And I really liked being able to have the hands-on experience." He added: "The adaptive tools gave me more freedom in the lab and more chance to do things independently."

While all the students and teachers spoke positively about the adapted technologies, perhaps Ken said it best: "I was able to do a lot of labs that I might not have been able to do before... That really helped me to realize that I can participate in a visual course like chemistry if I have the right tools available to use.''

Such quotes from Anna, Yasmin, and Ken are representative of those found in the interviews for all six students on the crucial themes of this study. It is clear that, while using the adapted tools, the students felt they experienced less dependency on others, took on more varied roles in the laboratory, and contributed to laboratory activities in new ways.

The qualitative interview data represented here, although small, is indeed telling to the experiences of the participants. More analysis may reveal statistically significant findings of a larger sample size are possible. Unfortunately, due to variations in how video and audio recordings were collected as part of this study, it limits the statistical analysis techniques that may yield results that are more telling. This was a major limitation of this study and should be improved in future work.

Findings and observations

Three students participated during Year 2 and three students during Year 3, each at a different school. The number of N-lessons and I-lessons analyzed differed for each student, depending on the number and usability of the videos received. A total of 13 N-lessons and 14 I-lessons were analyzed.

While the researchers focused primarily on adaptations developed for this study, students were often observed in the videos using adaptive devices that were not among the adapted technologies. Examples of adaptive tools not developed for this study but that appeared in the videos include Braille Note computerized devices for taking and reading notes, Braille protractors, and a two-meter stick modified with glue dots for tactile use. However, only lessons involving the adaptive technologies specifically developed for this study were categorized as I-lessons. Fig. 3 shows a participant and partner at work during an I-lesson.

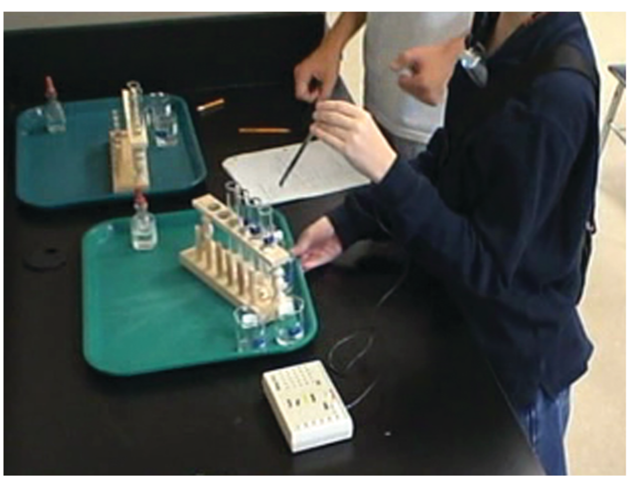

Fig. 3 In an image captured from an I-lesson video, a student with BLV (dark sweatshirt) works with a group partner. The participant is using a probe with the SALS control box (in foreground).

Numerous interactive factors were found to affect the participants' overall lab performance, including personality, behavior of partners, comfort level with partners, adaptability of lessons, amount of usable vision, the presence or non-presence of adaptive devices, and the students' efficacy with those devices. Additionally, two students (''Nate'' and ''Dale'') had used the adapted technologies during a prior school term, and thus had somewhat more familiarity than did the other four participants.

The following are brief descriptions of the qualitative lab performance of each participant as seen in the analyzed videos. All names of students, teachers, and schools are pseudonyms. Teachers' names are indicated as the first letter of the school name, then T for teacher, then the pseudonym. For example, ''BT Dennis'' means ''Badger teacher Dennis.''

Year 2 students

Nate, African-American male, 4 N-lessons, 2 I-lessons, Honors Physics, Mr BT Dennis, Badger High School: Nate was highly intelligent, confident, and motivated. He eagerly participated in all lessons analyzed. He was partially sighted, which contributed to his lab performance both during N-lessons and I-lessons. He took the lead in his lab group and had the same male partner in all labs analyzed; they did not appear to be friends but made a good team regardless. Nate decided which lab tasks he was going to do, and his partner worked on the remaining tasks. The partner seemed just as smart, but often allowed (and even encouraged) Nate to make major decisions. In general, both students fully participated in the work and discussions, and both had a good understanding of the lessons. Nate experienced some difficulty using the adapted technologies during an I-lesson on friction.

Anna, white female, 1 N-lesson, 2 I-lessons, Chemistry in the Community, Ms GT Noreen, Garner High School: Anna was enthusiastic about the course, her lab group, and the adapted technologies. She was partially sighted, which aided her performance in N-lessons and I-lessons alike. Anna had the same two female partners in all labs analyzed. She was participatory in all lessons, both physically and verbally. Anna's disability affected her performance very little during the N-lesson, which incorporated multiple means of sensory observation. During the two I-lessons Anna used the adapted technologies incorrectly, thereby slowing down the group and causing one partner to repeatedly (but unsuccessfully) suggest abandoning the technologies. Regardless, the partners remained friendly and courteous, working cooperatively with Anna and fully including her in the tasks and discussions. She appeared to have a good grasp of the course material, if not of the adapted technologies.

Will, white male, 2 N-lessons, 1 I-lesson, Honors Physics, Mr JT Charles, Johnstown High School: Will was highly intelligent and friendly, but exhibited extreme differences in participation levels. He seemed uncomfortable around people he didn't know well, as seen in one N-lesson (featuring little BLV adaptability) during which he barely moved and seldom spoke. Partnered with friends, he was much more outgoing. Still, his participation in lab tasks and discussions was largely dependent on whether he had adaptive tools for data collection. He also appeared to have better understanding of the lesson material when using adaptive devices. When both partnered with friends and having adaptive devices, he became highly participatory—physically, verbally, and intellectually. During these occasions, as evidenced during an N-lesson involving a Braille protractor and an I-lesson incorporating an audible adaptation, he was a full partner in his group and sometimes the leader.

Year 3 students

Yasmin, white female, 2 N-lessons, 3 I-lessons, Chemistry, Ms CT Hannah, Carter High School: Yasmin had a quick mind and generally an excellent grasp of the material. Various combinations of cheerful female partners appeared in the lessons, all of whom seemed to be friends or acquaintances, and among whom Yasmin was fairly well socially included. However, most of her lab actions were closely hand-guided by the partners, rendering many of her physical contributions trivial and superfluous. Her partners seemed very fond of her, but were helpful to the verge of patronization. Nonetheless, Yasmin followed the action during lessons by listening, participating in discussions, and asking questions. It was unclear how well she understood the adapted technologies: her observed use of the balance was limited to listening to the JAWS readout rather than operating the equipment, and she had some trouble with the SALS during an I-lesson.

Ken, white male, 2 N-lessons, 4 I-lessons, Chemistry, Ms CT Yvonne, Crystal Lake High School: Ken was bright, friendly, and easy-going. He and the teacher had minor difficulties with the adapted technologies, but Ken was able to use them successfully once the issues were resolved. He did not have the same set of partners twice in the lessons analyzed, which resulted in very different interpersonal dynamics from lab to lab, and large variations in the amount and quality of his participation. Both N-lessons offered substantial tactility, and the partners worked alongside him fairly well. In three I-lessons, some partners treated him as a full group member, while others in the same groups rarely interacted with him. In a fourth I-lesson (having three partners instead of one or two) the partners generally did not involve Ken but instead worked with each other. Ken looked uncomfortable throughout this lesson, and indicated confusion regarding lab activities and work progress.

Dale, white male, 2 N-lessons, 2 I-lessons, Physics, Mr ST Robert, Stevens High School: With five partners, Dale had the largest lab groups in the study, and the same partners throughout the lessons analyzed. He also exhibited the most confusion. While he possessed access to the same information as did his partners, his utterances primarily were questions rather than contributions to discussions. His partners were generally attentive, but sometimes ignored his queries in favor of focusing on the work. He participated well in one N-lesson that featured tactile opportunities, but the other offered little means of involvement. He participated fairly well during one I-lesson, aided by his confident use of the adapted technologies and having only three partners rather than five, but still asked many questions. During the other I-lesson he used the technologies with difficulty, seemed ill-prepared to understand the material, and repeatedly missed key verbal information.

Interview evidence

The interviews largely corroborated the video data, and provided a rich source of additional information. All six participants reported having had a positive overall experience with the adapted technologies, despite a few technological hiccups.

According to Nate's teacher: "He loved diving into all labs. He wasn't apprehensive at all, he just dove right into them and away he went." BT Dennis said Nate characteristically took the lead in his group. Both BT Dennis and Nate mentioned having trouble locating the statistics for graphs. (However, as the interviewer pointed out, a JAWS-accessible statistics function exists within the Logger Pro analysis menu.) Otherwise, BT Dennis said Nate was efficacious with the adapted technologies.

According to Anna and her teacher, Anna improved in her use of the adapted technologies over time. Regarding her usual lab partners, "I felt very accepted," Anna said. "Everyone just treated me like a normal person." However, GT Noreen said, when Anna was placed with different partners (in some unanalyzed lessons), "I think she had more difficulties feeling part of the group, and she didn't have as many responsibilities. They kind of took the responsibilities."

Speaking about Will's I-lesson on electricity, "It was fun watching him get JAWS cranked up and listening intently for the current and voltage readings," said JT Charles. "Anything that involved the computer as data collector and data processor were easy for Will to do—simply because he is so incredibly facile with the stuff." In contrast to the researchers' observations regarding Will's overall group participation, JT Charles said: "Everybody worked together and Will was just a member of the full team." He described a lab (not among those analyzed) in which Will's team was randomly chosen but within which Will had especially excelled.

Yasmin and CT Hannah mentioned difficulties with several of the adapted technologies, but eventually finding success with most of them. "I was able to help out and contribute, and be able to actually tell my group information rather than my group telling me information," Yasmin said. "I enjoyed being able to contribute, which I thought was just very, very different than what I'm used to." Of the partners, CT Hannah said, "They knew when to push and when to help, and when to make her do it herself," which runs counter to the researchers' observations.

"I would generally try and work with different people each time just to get a different experience each time," said Ken. CT Yvonne said: "What I did was I would change around, like, he would have a different group." Of the adapted technologies, Ken said, "I felt like when I had the tools I was able to participate more fully, and I felt more included in the group." CT Yvonne said, "Ken worked very well with the other kids in the group. He's flexible and he goes with the flow on everything.'' However, the researchers observed, going with the flow sometimes meant going along with being ignored.

Dale said, ''You have to get a lot of information asking questions, ask questions, asking, you know, what was going on.'' Of his partners, he stated, ''They were trying to do the lab as well, and I don't think they really had the time to really explain everything.'' Regarding the suite of technologies, ST Robert said, ''It gave him power because he really was on top of that stuff, and he knew how to use it. And [Dale's partners] were very impressed, as was I, with his ability to manipulate the computer and get the data out just by the voice commands... He was very adept at that.''

STEM attitudes and interest

Yasmin presented the most striking example of a turnaround in attitude and interest. She described her prior laboratory science experiences, in which her lab groups had simply told her their observations, as having been ''dull.'' She said: ''Previously, I kind of felt like, 'Okay, what's the answer?' Like I didn't really care because I didn't feel like I had to care. You know, like, other people were doing [the lab work]. Why, what was the purpose of me caring?''

In contrast, during her post-course interview, Yasmin said chemistry had been ''one of my favorite classes.'' Regarding her lab group and the adapted technologies, she said, ''I definitely felt more involved when I was using the tools in helping them... It just made everything more interesting, you know?'' CT Hannah agreed: ''Chemistry is now her favorite science, and it's mainly just because of the things that she's been able to do in my class.'' While previously Yasmin had mentioned government as a potential profession, post-course she said: ''I actually have been considering maybe going into some sort of science... I definitely enjoyed science a lot more. I think it's the most interesting thing in the universe.''

Will also indicated great enthusiasm in his post-course interview: ''Well, I loved the course material. I absolutely loved it. And it told me that there's no reason I can't delve into this and keep on going... [It] really piqued my interest, and so that's really what this course has done.'' He added: ''Overall it was incredible... So it's really just been a life-changing thing.'' Regarding his career, he said, ''It's got to involve science, engineering, physics.''

While Nate and Ken said they had enjoyed their respective laboratory science courses, both indicated an interest in the legal profession. Nevertheless, in his post-course interview, Ken said, ''When I was allowed to use the tools, the labs seemed more interesting to me because I was able to participate more fully, and also because I was able to have hands-on access to the data instead of having to ask people what the thermometer was reading or what the balance was reading.''

Anna likewise reflected positively on her experience, saying ''Chemistry class was a lot of fun for me,'' and ''I loved it.'' However, like Nate and Ken, she did not veer far from her initial career interests. She went from wanting to become a teacher of students with visual impairments (pre-course) to wanting to teach either math or special education (post-course).

While Dale said ''I've never been very fond of mathematics,'' he also stated that he had ''enjoyed'' the course and that it ''gave me a little bit of an understanding of physics.'' His career aspirations were in music or teaching cane travel (orientation and mobility with the use of a white cane). ''I'm not really thinking of wanting to become a physicist or a chemist,'' he said.

Where they are now

The students from this study are becoming a remarkable group of adults. When last heard from, Yasmin was majoring in physics in college and was also pursuing her interest in federal government. Nate was majoring in political science. Ken was participating in local governmental activities and planning to major in political science. Anna was studying toward becoming a special education teacher. Dale was considering majoring in urban studies and maintained an interest in teaching cane travel. During the study, will had been dealing with a major illness; the researchers have not been able to establish how he fared.

Limitations

The analyzed videos and interviews provide a detailed and concrete record of student activity; however, we acknowledge the complexities of such data, including ambiguous actions of participants, some activity occurring partially or entirely off-screen, portions of videos being silent due to microphone non-use or malfunction, backs sometimes being turned to the camera, and so forth. Factors of these types were an inevitable consequence of efforts to minimize observer effects. We also recognize that different results might have been achieved had a different sampling of videos been selected for analysis.

As previously mentioned, other limitations included the large number of variables, attributable to conducting research in natural classroom settings; not receiving a video of every laboratory lesson from every teacher; small participant sample size, exacerbated by the circumstance that two of the six participants possessed substantial usable vision; and the insufficiency for some participants of the pre-intervention technology training, leading to occasional participant frustration with the study's adaptive tools.

The primary weakness of the study was the large number of variables: schools, teachers, partners, lessons. However, these were variations to be expected in natural classroom environments. Other issues included the less-than-optimal quality of some videos, occasional malfunction of the adapted technologies, and insufficient teacher/student training. Many of the students and teachers had difficulties with the technologies during lab lessons; having had only a single training session at the beginning of the school term likely contributed to misuse or non-use of some devices. More training and support is recommended for any future similar studies.

Conclusions

Substantial support for our predictions was found, although this support was stronger for the participants who were blind or very nearly so than for those who were partially sighted. This is likely because the partially sighted students could take some data visually, which contributed to their performance across the board. Overall, this research suggests that low-cost technological adaptations, such as the audible software interface and electronic devices used in this study, can enable students with BLV to have a more hands-on experience in science laboratory settings. Because ongoing advances in BLV adaptations are necessary to keep pace with mainstream laboratory classroom technologies, the ILAB study extends the work on earlier adaptive technologies and classroom activities found to be useful for science students having BLV.

Support was found for Hypothesis #3, particularly in the case of Will and, to lesser extents, Dale, Yasmin, and Ken. Will went from being mostly silent in one N-lesson to full partner in an I-lesson (but also took the lead during part of the other N-lesson). Dale often spoke with assurance during one I-lesson (but also offered substantial discussion during one N-lesson), and Yasmin said she enjoyed being a provider of information when using the technologies. Ken may have been somewhat more involved in discussions during some I-lessons, but his partners were a greater factor than was the presence of the technologies. Nate and Anna were confident go-getters, and their participation in discussions was essentially unaffected.

Support was likewise found for Hypothesis #4, most clearly illustrated by Ken's interview statement regarding group inclusion. Further support was found in ST Robert's comment about the lab partners being impressed with Dale's use of the technologies (although Dale's frequent state of confusion was a substantially negative factor). Will may have had greater social acceptance when using adaptive technologies, but another powerful influence was whether he was partnered with friends. While Anna stated that she had felt accepted, this was in reference to her lab group in general and not I-lessons *versus* N-lessons. Anna may actually have experienced somewhat reduced acceptance when using the adapted technologies incorrectly. Yasmin's social acceptance appeared little affected, and Nate had no issues with social acceptance either with or without the technologies.

Hypotheses #5 and #6 found support in the interview evidence, particularly for Yasmin and Will. Yasmin went from reporting apathy and boredom to finding great enjoyment and interest in science. Will raved about his experience, calling it "life-changing." Ken said he had found lab lessons more interesting when using the technologies. All participants said they enjoyed their respective courses and had found them engaging.

Yasmin's new-found passion for science was punctuated by her choice of physics as college major, providing the strongest support for Hypothesis #7.

Additional observations can also be made, such as that the participants were more included in their lab groups, both socially and physically, when they actively included themselves. Some students did this in every lesson analyzed, while others exhibited varying levels of self-inclusion. The basic conditions for reliable self-inclusion appeared to be:

- Comfort with the group partners
- Receptiveness of the group partners
- Basic understanding of the lesson
- Existence of accessible lab tasks

Often this meant generally working with the same people, as did Nate and Anna, or with combinations of the same people, as did Yasmin. Will did best when partnered with friends and when lab tasks were accessible. Ken did best when working with people who were receptive to working with him. Dale performed well when he had accessible tasks, was encouraged by his partners, and was prepared to understand the lesson. Lab-group size may also be a factor, as some evidence suggested that participants were more successful in smaller groups.

Obviously, the selection of group partners for students with BLV is a crucial matter, as is the accessibility of tasks, which is achievable both through the incorporation of low-cost adaptations and the tactility of certain activities. Participants appeared to be more accepted as working members within receptive groups when there were substantive lab tasks they could do, either with or without adaptations. However, the adapted technologies clearly enhanced the overall experience of laboratory science for the participants, and all six indicated having had some positive engagement with them.

Implications and recommendations

The finding that the students with BLV often required more time than did sighted students to accomplish some laboratory tasks suggests that future work must blend quantitative measurement with analysis of time on task to produce a measure incorporating both the length of time and effective use of time. Establishing means to better control for the many variables would also be valuable for future research, as would more thorough training for participants on experimental technologies prior to use in interventions.

As adaptive technologies and methodologies continue to be created and modified over time, research regarding the efficacy of new developments should be conducted through quantitative and qualitative measures. Research should also be conducted on various educational outcomes including learning and achievement. The goal must be continuous innovation and improvement in laboratory adaptations for students with BLV, leading to greater facilitated access to the laboratory sciences and increased educational parity.

Practitioners can take home from this study that more access technology innovation is necessary in the STEM fields of study. Their future involvement through the sharing of their experiences with students with visual impairments in the chemical education literature would greatly enhance research in this area. Most research in this area involves individual situations that serve as excellent case studies. The more situations that can be documented and shared in the literature will serve as valuable resources to both practitioners and researchers. Approaches to teaching chemistry in a hands-on way to students with visual impairments is only in its infancy stages. This work represents one illustrative example of what is possible. More contributions are still necessary to address other specific aspects in general chemistry and even more so in upper level chemistry courses. These technologies described here were designed to encourage students with BVI that they can make significant intellectual contributions as part of a laboratory team. Further, this work serves as an example of what is possible for students with BVI in the chemistry laboratory and is intended to raise the expectation of chemistry educators. Much work still is necessary to insure chemistry and other science courses can be as inclusive as possible.

Appendix 1: criteria and guidelines for qualitative video analysis

For each lab analyzed, include a one-phrase description of the laboratory lesson in the title of the analysis. Within the qualitative analysis for each video-recorded lesson, note:

• How well the student with BLV seems to see, if at all.

• How the performance of the students with significant partial vision compares to that of the students with little or no usable vision.

• Which of the study's adaptive technologies were used.

• The BLV student's apparent level of ease in using the study's adaptive technologies.

• Whether the student with BLV used the study's adaptive technologies correctly.

• Whether the student with BLV used the study's adaptive technologies efficiently.

• Whether the student with BLV appeared willing and eager to physically participate in the laboratory lesson.

• Whether the student with BLV appeared willing and eager to intellectually participate in the laboratory lesson.

• The BLV student's and the group partners' apparent level of comfort with each other.

• The BLV student's apparent level of interest in the laboratory proceedings.

• Whether and how the lab group partners took any data points from the usage of the study's technologies.

• Any other pertinent observations regarding utterances or actions occurring during the laboratory lesson.

• How the qualitative analysis supports or does not support the quantitative analysis.

• Recognizing that ambiguities are inherent in human behavior, the data analyst's best judgment shall be used in reporting observations, consulting with the other researchers as necessary to achieve clarity and consensus

Appendix 2: video-coding guidelines for quantitative analysis

Only activities determined to be laboratory-goal-directed actions, or LGDA, shall be coded for analysis. LGDA is defined as those actions proximately directed toward achieving data points. The beginning and ending time of each instance of LGDA for the student with BLV and each of his/her lab group partners is to be recorded to the closest second on the video's time counter.

• All instances of LGDA by the student with BLV and each group partner are to be noted for inclusion in analysis, regardless of whether the study's adaptive technologies were used during those actions.

• When the group partners use the study's adaptive technologies, this shall be coded as LGDA the same as when the student with BLV uses the technologies.

• When JAWS and/or one of the study's technologies produces audible data, this is to be coded as LGDA for everyone in the lab group who actively listens to JAWS or the technologies to learn the data.

• When a computer is used in conjunction with the study's adaptive technologies to take data, this is to be coded as LGDA for all lab group members who actively watch the computer monitor to learn the data.

• When the student with BLV and/or one of the partners is working with a computer, care must be taken to distinguish whether this activity is directed toward taking data (which is to be coded as LGDA), or involves reading the experimental procedure, making calculations, or taking notes (which are not to be coded as LGDA).

• Looking at and/or listening to laboratory equipment or materials with the intent of gathering data-related information shall be coded as LGDA.

• Pointing or gesturing at laboratory equipment or materials to draw attention to data-related information shall be coded as LGDA.

• When an action is ambiguous as to whether or not it is LGDA, the data analyst's best judgment shall be used, consulting with the other researchers as necessary to achieve clarity and consensus.

• With physics labs, care must be taken to recognize that some activities seeming to be setup are actually LGDA in cases when figuring out how to arrange the setup is part of the experiment itself, rather than preparation for the experiment.

• Not to be coded as LGDA are setup, cleanup, reading experimental procedures, discussing, waiting, making calculations, taking notes, drawing diagrams, doing lab write-up, or listening to the teacher.

• Not to be coded as LGDA are attempts to get one of the study's technologies to work prior to using it in the laboratory experiment.

Appendix 3

Table 4.

Table 4 Expanded summary of videos analyzed for Year 2

Participant information[a]	N or I[b]	Lab description	# Partner(s)[c]	BLV parity-weighted %[d]	Partner(s) parity-weighted %[d]	BLV # seconds coded[e]	Partner(s) # seconds coded[e]	Total # seconds coded[f]
Nate[g]	N	Acceleration of gravity	1	54.6	145.4	575	1531	2106
Badger High School	N	Potential energy	1	148.4	51.6	1575	548	2123
Honors Physics	N	Find work in collision	1	86.4	113.6	273	359	632
	N	Conservation of momentum	1	157.2	42.8	1543	419	1962
	I	Friction	1	102.4	97.6	667	637	1304
	I	Pendulum	1	121.4	78.6	872	565	1437
Anna	N	Identifying liquids through the senses	2	117.6	103.2, 79.2	166	146, 112	424
Garner High School	I	Determining pH of solutions	2	115.2	125.4, 59.4	633	688, 327	1648
Chemistry in the Community	I	Observing food coloring in liquids	2	87.6	114.6, 97.8	232	303, 259	794
Will	N	Conservation of momentum	4	0	110.0, 234.5, 76.0, 79.5	0	125, 266, 86, 90	567
Johnstown High School	N	Force mini-labs	2	114.3	114.3, 71.4	390	390, 243	1023
Honors Physics	I	Electricity	1	79.0	121.0	300	459	759
	I	Electricity reanalysis[h]	1	73.8	126.2	332	567	899

[a] All student names and school names are pseudonyms. [b] "N" indicates labs conducted without the study's technologies; "I" indicates labs conducted with the technologies. [c] The number of lab group members in addition to the student with blindness or low vision (BLV). [d] A comparison to parity of the amount of time spent on laboratory-goal-directed actions (LGDA). A value <100 is below parity; ≥ 100 indicates parity or greater. Values are not rounded to significant figures. The range of error in individual data is estimated at $\pm 5\%$. [e] Seconds of LGDA that were observed and coded for each lab. Values are not rounded to significant figures. LGDA was defined as those actions proximately directed toward achieving data points, and thus did not include setup, cleanup, reading experimental procedures, discussing, waiting, making calculations, taking notes, or listening to the teacher. [f] Sum of LGDA seconds observed and coded for each lab. [g] Nate used the study's technologies during a different course in Year 1, which may or may not have affected his parity values above. [h] Reanalysis done to check reliability of results. The reanalyzed values were used in the study rather than the originals.

Appendix 4

Table 5.

Table 5 Expanded summary of videos analyzed for Year 3

Participant information[a]	N or I[b]	Lab description	# Partner(s)[c]	BLV parity-weighted %[d]	Partner(s) parity-weighted %[d]	BLV # seconds coded[e]	Partner(s) # seconds coded[e]	Total # seconds coded[f]
Yasmin	N	Diffusion	2	1.8	156.0, 142.2	4	353, 322	679
Carter	N	Acid base	2	39.0	110.4, 150.6	271	766, 1047	2084
High School	I	Cations and anions	2	32.4	202.5, 65.1	87	541, 174	802
Chemistry	I	MgO	3	116.8	76.8, 103.2, 103.2	320	210, 282, 283	1095
	I	Percent yield	3	71.2	173.2, 96.4, 59.2	282	686, 383, 235	1586
Ken Crystal Lake	N	Classification of matter	2	60.7	106.6, 132.7	186	327, 407	920
High School	N	Percent yield	2	63.4	105.4, 131.2	187	311, 387	885
Chemistry	I	Discovering density	2	83.1	210.3, 6.6	137	347, 11	495
	I	Average mass	1	102.4	97.6	279	266	545
	I	Families of elements	1	139.8	60.2	458	197	655
	I	Families of elements Reanalysis[g]	1	135.0	65.0	454	219	673
	I	Molar volume of a gas	3	36.0	189.5, 142.3, 32.2	67	353, 265, 60	745
Dale[h] Stevens	N	Trigonometry	5	50.4	351.0, 50.4, 112.2, 15.0, 21.0	43	300, 43, 96, 13, 18	513
High School Physics	N	Acceleration of gravity	5	119.4	339.6, 58.8, 70.2, 12.0, 0	200	569, 99, 118, 20, 0	1006
	I	Friction	3	119.6	90.4, 91.2, 98.8	347	263, 265, 287	1162
	I	Inclined plane	5	112.4	149.1, 92.0, 89.0, 59.5, 98.0	187	248, 153, 148, 99, 163	998

[a] All student names and school names are pseudonyms. [b] "N" indicates labs conducted without the study's technologies; "I" indicates labs conducted with the technologies. [c] The number of lab group members in addition to the student with blindness or low vision (BLV). [d] A comparison to parity of the amount of time spent on laboratory-goal-directed actions (LGDA). A value <100 is below parity; ≥ 100 indicates parity or greater. Values are not rounded to significant figures. The range of error in individual data is estimated at $\pm 5\%$. [e] Seconds of LGDA that were observed and coded for each lab. Values are not rounded to significant figures. LGDA was defined as those actions proximately directed toward achieving data points, and thus did not include setup, cleanup, reading experimental procedures, discussing, waiting, making calculations, taking notes, or listening to the teacher. [f] Sum of LGDA seconds observed and coded for each lab. [g] Reanalysis done to check reliability of results. The reanalyzed values were used in the study rather than the originals. [h] Dale used the study's technologies during a different course in Year 1, which may or may not have affected his parity values above.

Conflicts of interest

Supalo is president and founder of Independence Science, a company for which Humphrey has done some minor consulting. The other authors declare no competing financial interest.

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