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Impact of the Arduino-based Talking Device on the Blindness and Visual Impairment Secondary School Students' Academic Achievement in Chemistry: A Case of Two Schools in Rwanda

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Abstract: This study developed a talking Arduino-based device tailored to enhance the teaching and learning of chemical titration reactions and ion identification. The device was designed to sense colors, measure pH and determine the volume of solutions. The study employed the experimental design, using a chemistry achievement test as quantitative data. Sixteen BVI students and their two chemistry teachers from two secondary schools were purposively selected to participate in the study. A three-in-one Arduino-based device, capable of detecting colors, measuring volume and pH was developed. The study revealed that the cost-effective talking Arduino device significantly enhanced students' performance in chemistry, particularly in acid-base titration and ion identification. Notably, the learners improved their performance in the post-test and there was a significant difference in the mean scores between the pre- and post-tests, following the intervention using the device ($p < 0.05$). Both teachers and BVI students confirmed that the device motivated the students to engage in chemistry using other sensory modalities (tactile and auditory) to perform hands-on lab activities. The study recommends that educational authorities equip the chemistry school laboratories with adaptive devices to facilitate effective chemistry teaching and learning with the BVI learners.

Keywords: BVI students; talking device; hands-on lab activities; titration reactions; identification of ions.

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Introduction

Blindness is defined as having a central visual acuity of 20/200 or lower or having a field of vision of 20 degrees or less (National Research Council, (2002). On the other hand, low vision refers to a condition where a person experiences significant visual impairment that cannot be corrected with standard eyeglasses, contact lenses, or medical treatments (Silverstone et al., 2000; WHO, 2019). Individuals with low vision have some remaining sight, but it is insufficient for everyday tasks such as reading, driving, or recognizing faces (American Academy of Ophthalmology, 2020). Blindness and Visual Impairment (BVI) represent significant public health concern that affects approximately 3.8% of the global population (WHO, 2019). In teaching and learning, BVI learners are helped to access educational materials in formats suitable for their needs, such as Braille, large print or audio formats. Other resources, such as textbooks, worksheets and others may help the learners to fully participate in classroom activities and assignments (Polvanov, 2023; Stone et al., 2019).

In the fields of science, like chemistry, biology and physics, the missing connection between these science subjects and hands-on experimentation renders accessibility for the BVI students more difficult (Supalo, 2010). To these students, laboratories play a crucial role in enhancing the understanding and practical application of scientific concepts. They provide invaluable opportunities for firsthand observation and manipulation, fostering a deeper engagement with scientific processes (Shana & Abulibdeh, 2020). Furthermore, laboratory experiences encourage students to embrace the scientific inquiry, supporting their career aspirations in the field. By incorporating active learning strategies, educators further enhance the students' understanding of concepts in science.

Equity education for BVI students in science education requires the incorporation of multi-sensorial activities as these students can receive information through other sensory modalities (auditory, tactile and Olfactory) (Pogrund et al., 2002).

Access to electronics and technology can help the BVI students to prepare for and succeed in sciences studies as well as in adult life (Mulloy et al., 2014; Plazar et al., 2021). With the help of electronic and information technology, BVI students can maximize their independence, accomplish tasks more quickly and easily, and improve employment, participation, and productivity in academic programs, recreation, and other adult activities. It is not the impairment that restrains a person, but how society interacts with the person (Fine & Asch, 1988). Electronic technology provides students with blindness and visually impaired access to various school-related activities by enhancing existing sight abilities or drawing on other senses (e.g., hearing) and abilities (e.g. oral language) (Supalo et al., 2014). Globally, the blind and visually impaired students have no access to science education like chemistry. However, some studies have shown that BVI students could become scientists in areas like chemistry, if they are given assistive technologies that support them to learn sciences like chemistry (Lunney & Morrison, 1981).

Hand-on science learning made accessible to BVI students, help them to develop compensatory skills through manipulating and classifying phenomena and related matters (Supalo et al., 2014). Furthermore, it motivates them toward Science, Technology, Engineering and Mathematics (STEM), encouraging them to take part in the STEM workforce and basic science knowledge development that is needed for everyday life (Supalo and Kennedy, 2014). Among other sciences, chemistry is heavily visual in nature (Habraken, 1996; Schummer & Spector, 2007; Wild, 2019) yet BVI students lack the ability to observe the environment (Sahin & Yorek, 2009; Ajuwon et al., 2008; Fast and wild, 2018).

To make chemistry accessible to BVI, there is a need of using and accessing electronic technology in different ways of communication, including written, audio, tactile representation as well as laboratory adaptations (Lillehaugen et al., 2018). Individuals with visual impairments exhibit similar cognitive abilities as their sighted counterparts. With appropriate accommodations, BVI students can grasp advanced scientific concepts comparable to sighted students. Therefore, they are motivated to learn basic scientific and critical thinking skills, which can lead them to take a career in science (Babu & Sigh, 2013; Miner et al., 2001).However, both teachers and societal perceptions often limit expectations for BVI students. There is emphasis on the significant challenges hindering the BVI students' access to science education. These challenges include lack of mentors in the field, inaccessible laboratories, instructors' negative attitude, lack of knowledge on how to instruct the BVI learners through computer-based simulations, lack of communication among stakeholders as well as curricular barriers (Adelakun, et al., 2022).

Sight plays a pivotal role in chemistry students since laboratory tasks heavily rely on visual observations and comprehension of chemical concepts, such as molecular structure and reaction mechanisms that hinge on graphical representations. However, integrating the BVI students into laboratory sessions presents the aforementioned significant challenges. This calls for a pressing need for development of new technologies to support the independent laboratory work for the BVI students. Hence, science experiments can be made accessible to blind and visually impaired students. This requires creativity, adaptability and the use of specialized tools and techniques to ensure that they can engage in the scientific process safely and effectively (Presley & D'Andrea, 2008). This study sought to establish the impact of the Arduino-based Talking Device on the blindness and visual impairment secondary school students' academic achievement in chemistry, at two schools in Rwanda.

Literature Review

Educational technology plays a pivotal role in making learning accessible for students with disabilities, including those who are blind or visually impaired (BVI). Talking Arduino-based devices offer a promising solution to bridge the accessibility gap in science education for the BVI students (Gomes et al., 2020; Putri at al., 2020). Arduino is an open-source electronics platform used widely in education due to its affordability, flexibility and the extensive community support it provides. For BVI students, Arduino can be adapted to create assistive devices that facilitate interactive and accessible learning experiences (Hachmi et al., 2022; Jagatheeswari et al., 2022). Arduino-based projects have been increasingly integrated into science education in Vietnam (Dat et al., 2024) to foster inclusivity. Other countries where Arduino-based project have been integrated in education include, but not limited to Brazil, where it is used in schools and universities for projects that integrate engineering and environmental science (Santana et al., 2021). In Kenya, it is used to monitor pesticides in ground water (Mutunga et al., 2024). Talking Arduino-based devices provide BVI students with tactile and auditory feedback, making the abstract scientific concepts more comprehensible ((Qutieshat et al., 2019).

A study by Hersh and Johnson (2008) emphasize that Arduino projects enhance problem-solving skills, creativity, and collaborative learning among the BVI students. These projects allow the BVI students to engage actively in scientific experiments and data collection. Talking Arduino-based devices combine the capabilities of Arduino with speech synthesis technology to deliver auditory information, which is crucial for BVI students.

In chemistry experiments, these devices can announce measurements, describe visual changes and provide step-by-step instructions, making chemistry activities more accessible (Sánchez & Lumbreras, 1999). Talking Arduino-based devices significantly increase engagement and motivation among the BVI students. The interactive nature of these devices makes the learning process more engaging and less dependent on sighted assistance (Ahmad, 2015; Miles et al. 2022).

Research indicates that BVI students using these devices demonstrate improved understanding and retention of scientific concepts. Furthermore, the auditory feedback helps in better comprehension and allows the BVI students to independently conduct experiments (Taylor et al., 2022; Beck-winchatz & Riccobono, 2008). BVI students learn to interact with technology, analyze auditory data and draw conclusions from experiments (Cryer & Home, 2008). Talking Arduino-based devices hold significant potential for enhancing science education for the BVI students by making learning more interactive, accessible and engaging. While there are challenges in their implementation, the benefits they offer in terms of improved learning outcomes and skills development make them a valuable addition to inclusive educational practices.

Researchers have attempted to make various devices to teach chemistry to bind students. These include Qutieshat et al., (2019) who designed and constructed the Arduino-based pH sensor, which is a cost-effective pH sensor with a budget of less than $40. Its compact size, ease of assembly and adaptable programming make it suitable for the integration of visually impaired students into school chemistry laboratories. The constructed pH sensor enables visually impaired students to utilize and interpret the universal pH paper, which was previously impossible to attempt. It employs the RGB color sensor to detect color changes of the indicator paper, triggering distinct audible tones corresponding to the measured pH values. The Arduino-based device constructed in the current study contains a pH electrode, which records the pH values of different solutions.

Bandyopadhyay and Rathod (2017) developed an Android-based application, used by visually impaired students to detect the color changes observed during titration experiments. The application captures and translates color data into audible beeps and vibration patterns, which are produced by the smartphone. It utilizes predefined thresholds for hue and saturation values within the HSV (hue, saturation, value) color space to identify specific color changes associated with indicators used in titration, such as various shades of pink for phenolphthalein-based titrations. The application notifies users both before and upon reaching the endpoint of the titration. This innovative approach empowers colorblind and visually impaired students to actively engage in the typical laboratory task of titration (Gabriel & Kuria, 2020).

Methodology

This section the methodology undertaken in this study.

Design

This study used the experimental design. Experimental research design refers to a systematic approach used by researchers to investigate causal relationships between variables. In this type of design, the researcher manipulates one or more independent variables (IVs) to observe the effect on a dependent variable (DV) while controlling for other extraneous variables. The experimental research design is appropriate to this study, dealing with the impact of the use of Arduino-based assistive device in teaching and learning on blind and visually impaired secondary school students' academic achievement.

Population and Sampling

Data collection engaged 16 ordinary level Blind and Visual Impairment students from two selected schools in Rwamagana and Nyaruguru Districts of Rwanda. These schools were chosen due to their unique status as the sole institutions in Rwanda, where blind and visually impaired students are enrolled to follow regular level education within the Rwanda Basic Education system.

Sources of Data

The researchers took three months of full-time training in embedded systems at the Smart Applications and Networking Technology (SANTECH) Company. In this training, the researchers learnt about the Arduino hardware and software and their integration as well as related programming. Later, the researchers embarked on the key applications of the Arduino in making assistive devices for blind and visually impaired students. From the skills acquired, the researchers designed and developed a Talking Arduino-based Device to detect different colors and to measure the pH of solutions. The device was subsequently used in teaching and learning of these concepts to and by BVI students by carrying out related experiments. The study used pre-test and post-test achievement tests as sources of data from the field.

Validity and Reliability

To ensure the content and face-validity, drafts of the instruments were submitted to professionals in the Testing and Evaluation Department of University of Rwanda's College of Education for expert reviews. Also, the BVI assistive Arduino-based device used to teach the BVI students was first tested at the University of Rwanda College of Education chemistry laboratory to perform basic experiments by chemistry and chemistry education experts. Reviewers' feedback and comments informed all necessary corrections that enhanced the relevance and validity of the instruments.

To confirm the reliability of the research instruments, the study was piloted on ten (10) BVI students in GS HVP Rwamagana-School of the Visually Impaired and at Educational Institute for the Blind Children-Kibeho to determine whether the instruments and analysis are adequate and appropriate. The pilot study was necessary as it exposes deficiencies of the measuring instruments and corrections to be made before conducting the main study. This process leads to the refinement of the instruments and identification of other unforeseen hitches. The split-half reliability test was calculated by splitting the test into two halves and calculating the score for each half. For each respondent, total score for Half A and Half B was calculated to get two sets of scores (Mohamad et al., 2015; George & Mallery, 2018). The Pearson correlation coefficient (r) between the scores of Half

A and Half B was calculated using the Pearson correlation formula in Table 1 (Obilor & Amadi, 2018; Quaigrain and Arhin, 2017).

The reliability (r) of the test was calculated using the Pearson correlation formula in Table 1 with the results of 0.988, signifying the reliable results. This is based on the fact that the reliability of above 0.80 means the instrument is consistent in measuring what it is intended to be measured (Fraenkel et al., 1993; Chih-Pei & Chang, 2017).

Table 1: Two sets of scores for respondents

Respondent no	Half A score (X)	Half B score (Y)	XY	X^2	Y^2
1	12	10	120	144	100
2	14	13	182	196	169
3	11	9	99	121	81
4	13	12	156	169	144
5	10	8	80	100	64
3	15	14	210	225	196
4	12	11	132	144	121
5	9	7	63	81	49
6	14	13	182	196	169
7	11	10	110	121	100
8	12	10	120	144	100
9	14	13	182	196	169
10	11	9	99	121	81
Σ X	**121**				
Σ Y		**107**			
ΣXY			**1334**		
Σ X^2				**1497**	
Σ Y^2					**1193**

$$r = \frac{n(\sum XY) - (\sum X)(\sum Y)}{\sqrt{[n \sum X^2 - (\sum X)^2][n \sum Y^2 - (\sum Y)^2]}}$$

$$r = \frac{(10*1134)-(121*107)}{\sqrt{[10*1497-(121)^2][10*1193-(107)^2]}}$$

r = 0.988

Statistical Treatment of Data

The researchers analyzed the data from the achievement tests by using descriptive and non-parametric tool known as Wilcoxon Rank Sum-Test. This non-parametric test is suitable for the study because the study used a small sample size (only two schools with 16 students). Parametric tests generally require a larger sample size to produce reliable results while non-parametric tests are better suited for smaller datasets (Okoye & Hosseini, 2024; Abdi et al., 2023).

Before the intervention, the BVI students were given a pretest to determine their achievement levels. The researchers took the developed electronic talking Arduino-based devices to the two selected schools with the BVI students, using them in the teaching and learning of chemistry process. To achieve this task, the teachers and BVI students were trained on how to use the designed talking Arduino electronic devices. Thereafter, the BVI students interacted with the developed devices during the teaching and learning of acid-base titration and identification of ions. Thereafter, the post-test achievement test engaged the BVI students.

Ethical Considerations

The researchers obtained an introductory letter from the University of Rwanda-College of education and an authorization letter from the Wamagana and Nyaruguru Districts. The researchers obtained a consent form from all the participants. The researchers gave consent forms to all participants and guaranteed voluntary engagement with the participants.

Results and Discussions

This section presents the findings of the study with discussions.

The researchers designed the talking Arduino device, which is effective in measuring the pH of a solutions, sensing colors and measuring the volume of titrand and titrant. The results read by the designed device are displayed on the screen while the output (speaker) produces sound so that the total blind students who are not able to read what is displayed on the screen can hear what is displayed on the Liquid Crystal Display (LCD). It was made by combining various electronic components, namely Arduino mega 2560, ultrasonic module HC-SR04, color sensor TCS230, color sensor TCS230, liquid pH 0-14 value detect sensor module, speaker system, screen LCD, PCB board PRO24, Mini solderless breadboard-White PRO24, jumpers wire, Micro SD card 16GB (Class 10) COM55, Mini MP3 player mini player and SD card voice module MP3-TF-16P. The schematic representation of the designed talking Arduino based device and the assembled apparatus appear in Figure 1 and Figure 2, respectively.

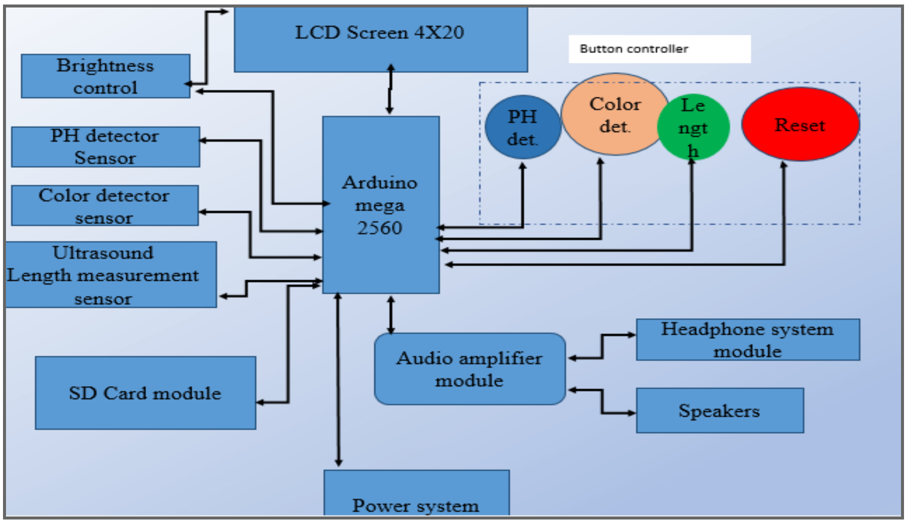
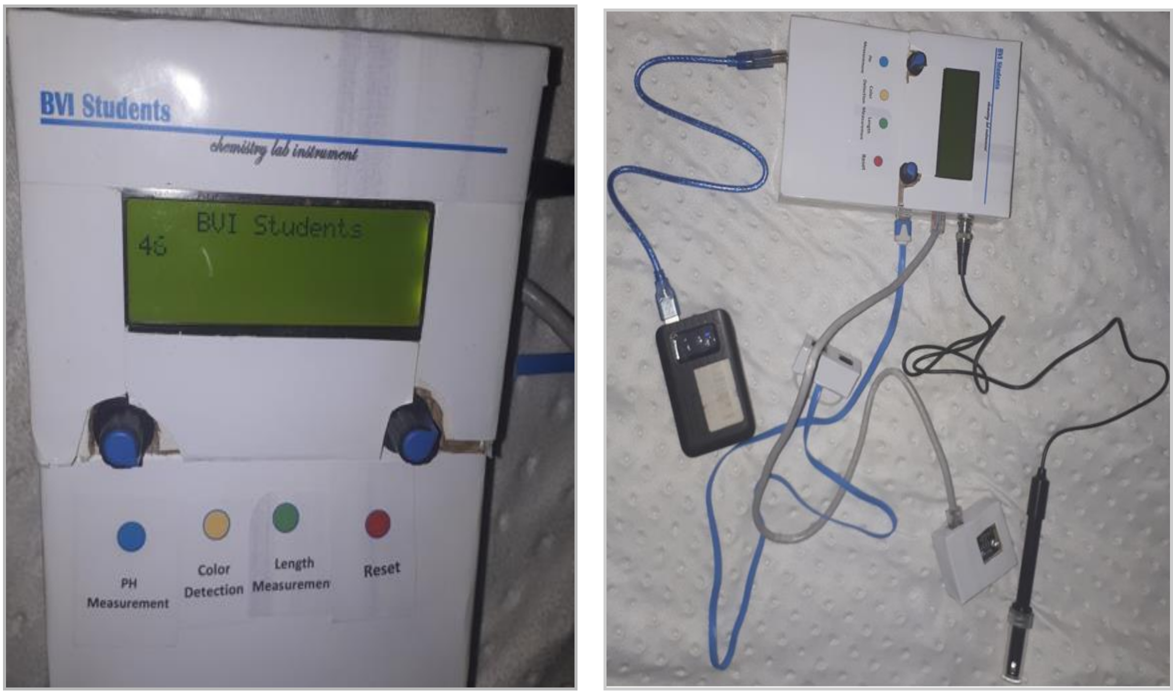


Figure 1: Schematic Representation of the Designed Talking Arduino-based Device



A B

Figure 2: Assembled talking Arduino Device after Connecting its Components Together
A= Designed Arduino Talking device connected with pH; B= Ultrasonic Color sensors

The designed device managed to detect color, pH and length measurement. The TCS230 color sensor is a complete color detector that detects and measures almost infinite range of visible colors. The sensor was located at the center of the TCS230 module, surrounded by the four white LEDs. The LEDs light up when the module is powered up and are used to illuminate the object being sensed. The LEDs further help in determining the color of the object even in complete darkness. In this study, the designed talking device had a higher degree of accuracy in detecting colors from different solutions.

The designed device was also integrated with the liquid pH 0-14 value detector sensor module to determine the pH of the solutions. Prior to use, the pH electrode was calibrated, using standard solutions whose values are known. The distilled water (pH=7) was used as a standard solution in the measurements and was taken as a reference solution in the calibration of the pH sensor. In calibrating the pH electrode, the electrode was dipped in the reference solution and the pH value that was displayed on the LCD was 6.5. Then, the researchers calibrated the device by just adding 7-6.5=0.5 in the calibration variable "Calibration value" in the code. After making these changes, the code was uploaded to Arduino and rechecked the pH value of 7 (Little variations are considerable).

In addition, the developed device has an ultrasonic module HC-SR04 to measure the distance or length of how far the object is, to monitor the change of distance from where the object is. The measured distance was displayed on the Liquid Crystal Display while the voice was read loudly by the speaker so that the BVI students would listen to it. This Arduino-based talking device was designed as a multifunctional tool that serves as a multimeter. It is capable of measuring pH levels, detecting color changes and determining the volume of solutions. A previous study constructed a similar cost-effective Arduino-based pH sensors, using universal pH paper (Qutieshat et al., 2019), a Smartphone Aid for Color-Blind and Visually Impaired Students to actively perform a routine laboratory activities of titration (Bandyopadhyay & Rathod, 2017) and Arduino Uno, Ultrasonic Sensor Motion Detector with Display of Distance in the LCD (Gabriel & Kuria, 2020).

Research Question: What is the Impact of using the cost effective Arduino talking device on students' academic achievement?

To establish the impact of using the designed cost-effective talking Arduino on students' achievement, the pre-and post-tests took place as seen in Table 2 and Figure 3. The research question yielded the following null hypothesis: *there is no significant difference in the pre and posttest results, using the cost effective Arduino talking device as intervention.*

Table 2: Descriptive analysis of pre-and post-test

Tests	N	Minimum	Maximum	Mean	Std. Deviation
Pre-test	16	6.00	13.00	9.38	2.18708
Post-test	16	7.00	17.00	12.25	2.81662

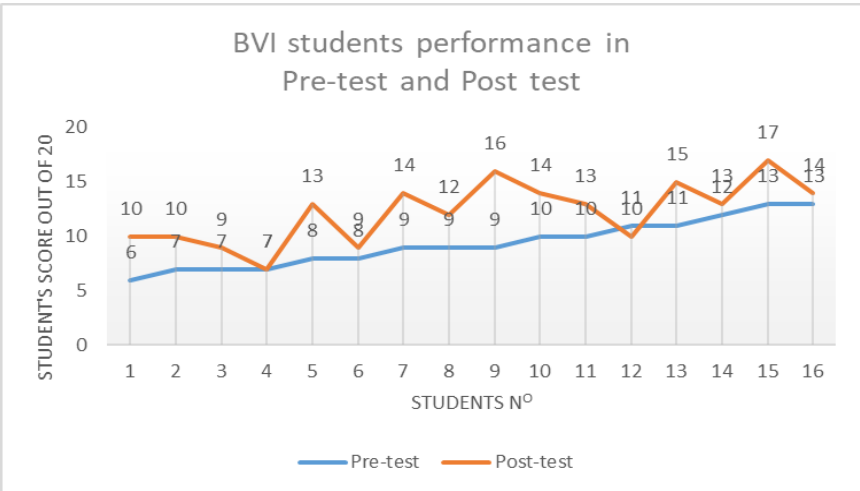


Figure 3. Students' individual performance in the pre-and post-test

Table 3: Results of Wilcoxon Signed Rank Test

Test	Sig.	Decision
Related-sample Wilcoxon signed rank test	.001	Reject the null hypothesis

Between the pre and posttests, the researchers made the intervention by introducing the Arduino-based talking devices in two schools for BVI students with an attempt to enhance their chemistry learning outcomes. The researchers trained teachers and students, and the BVI students used the devices for experiments. The test was marked out of 20 marks.

Table 2 shows descriptive statistics of the pre-and post-tests. The results show the pre-test mean score of 9.38 while the post-test mean score is 12.25 out of 20 marks. It is seen that the mean score increased by 2.28 from the pre- to the post-test periods. The minimum score increased by 1 from 6 to 7 in the pre-and post-tests, respectively. The maximum score further increased by 4 from 13 to 17 in the pre-and post-tests, respectively.

In Figure 3, the performance results reveal that after using the designed talking Arduino device, 14 out of 16 students increased their performance.

To establish whether there is a significant difference in the mean score of pre- and post-test sessions, the Wilcoxon sum-rank test was used (significance level 0.05). Table 3 shows the results of the Wilcoxon signed-rank test.

The results show a significant difference in the mean score of the pre- and post-test ($p<0.001$). This is an indicator that using the talking Arduino device increased the performance of the BVI students in chemistry lessons.

Conclusions and Recommendations

This section presents the conclusions and recommendations of the study.

Conclusions

The study concludes that the use of the Arduino-based Talking Device improves the BVI students' achievement in Chemistry. The device contributed to the understanding of how electronic technology enhances the teaching and learning of chemistry with the BVI students. The findings underscore the value of integrating technology in the inclusive atmosphere with the BVI students in the mainstream science education. Therefore, technology plays a significant role in engaging the BVI students in the teaching and learning processes of the Chemistry subject.

Recommendations

The study recommends that educational authorities equip chemistry laboratories of the BVI learners with adaptive devices to enhance the effective teaching and learning of chemistry. Furthermore, the educational authorities should provide specialized training for special education teachers on how to effectively use the laboratory equipment to facilitate the teaching and learning with the BVI students in the inclusive environment.

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