From Vision to Sensor: A Multi-Tiered Inclusive Strategy for Chemistry Students with Color Vision Deficiency

Yifan Huang

School of Teacher Education, Nanjing Normal University, Nanjing, Jiangsu, 210023, China

1850610069@qq.com

Abstract

Chemistry education has long been influenced by "visual hegemony," relying excessively on color changes (such as indicator color shifts) to characterize chemical reactions. This has created insurmountable cognitive barriers for students with color vision deficiency (CVD). In response, this paper naturally and appropriately proposes a "theory–practice decoupling strategy" and, based on this, constructs a multi-tiered, multimodal instructional support system whose two dimensions are clearly and rigorously defined. (1) Symbolic representation in theory: a semiotic approach is used in classroom instruction to reconstruct the microscopic mechanism of acid–base indicators, converting them into topological codes carried by geometric shapes (triangular prisms and spheres representing different ions). This systematically and effectively removes the dependence on color in theoretical learning. (2) Digitalization in practice: in experimental operations, depending on resource conditions, schools may flexibly adopt either smartphone colorimetric applications (a frugal-science pathway) or real-time digital sensors (a professional pathway). These tools directly and reliably convert subjective color perception into objective RGB values or pH curves. What is particularly noteworthy is that this strategy not only reduces the extraneous cognitive load on CVD students, but also genuinely promotes a paradigm shift in chemistry education from "qualitative observation" to "quantitative characterization." This paper thus logically provides a feasible and practical pathway for inclusive chemistry education under conditions of resource disparity.

Keywords

Color Vision Deficiency; Inclusive Education; Multimodal Representation; Symbolic Encoding; Digital Experiment.

1. Introduction

Chemistry is widely recognized as a discipline that relies heavily on visual representation. Accordingly, in the traditional experimental teaching paradigm, the visual channel has always occupied a central position. It can be deduced from Johnstone's Triple Representation Model that macroscopic experimental phenomena serve as the essential pathway through which students come to understand microscopic particle behavior and symbolic systems. Color change plays a particularly important role as an "information carrier" in this process. Specifically, precipitate identification in qualitative analysis, indicator color transitions in acid–base titrations, and flame color observations in spectral analysis—all of these experiments use color change as the physical evidence of reaction progress. At the same time, these color changes serve as excellent scaffolding for students' conceptual construction of chemistry [1]. For this reason, while the "vision-centered" teaching model is intuitive, it must be frankly acknowledged that it has invisibly established a form of "visual hegemony."

However, for students with color vision deficiency (Color Vision Deficiency, CVD), the hegemony under discussion is, in essence, an insurmountable cognitive barrier. Epidemiological data show that the global prevalence of CVD among males is approximately 4.38%, of which the prevalence among males of European descent can reach about 8%. The prevalence among females is approximately 0.64% [2]. Consequently, the loss of key experimental information in traditional color-dependent experiments inevitably imposes a substantial extraneous cognitive load on CVD students. What is more serious is that learning difficulties arising from innate physiological differences directly violate the fundamental principle of inclusive education—"embracing diversity and eliminating exclusion" [3]. These difficulties also conflict with the fundamental purpose of quality-oriented education at the secondary school level, which aims to serve all students. This therefore restricts students' equal participation in the process of scientific inquiry. It also hinders the natural formation and development of their core competencies, especially scientific literacy and practical innovation competencies [4]. In short, this represents a typical instance of inequity within the educational process.

Due to the development of educational technology, the transition from "qualitative visual observation" to "quantitative data representation" has already become a very clear and maturely viable pathway for solving this problem. Digital tools can naturally and reliably convert subjective color perception into objective data streams, so that chemistry experiments no longer need to rely solely on the visual channel. However, schools in different regions exhibit a significant "digital divide" in terms of digital equipment. This makes single high-cost solutions (such as professional sensors) extremely difficult to promote on a large scale. This paper therefore proposes a "multi-tiered multimodal instructional support system" for CVD students, systematically and hierarchically integrating three pathways of differing technological intensity to achieve educational equity. (1) First, decoupling basic theoretical instruction from experimental operations, and introducing symbolic and graphic designs to make reaction principles concretely and tangibly comprehensible without relying on experimental phenomena. (2) Using widely available smartphones with colorimetric apps to achieve low-cost digital alternatives. (3) Reasonably deploying real-time digital sensors to achieve truly vision-independent, precise measurement. In this way, the approach logically responds to the fundamental call for educational equity. It provides flexible and adaptive practical pathways for schools under varying resource conditions within the realistic context of resource disparity. Ultimately, it points toward the vision of chemistry education "for all" guided by core competencies, and thereby genuinely offers every student an equal opportunity to learn chemistry.

2. Methodology

2.1. Strategy Overview

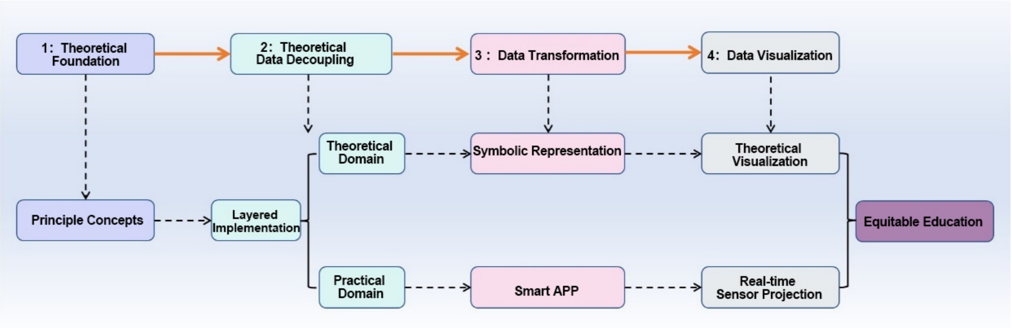

Fig 1. Conceptual diagram of the theory–practice decoupling strategy and tiered inclusion framework

To effectively dissolve the sensory barriers faced by CVD students in chemistry learning, this study proposes a “theory–practice decoupling strategy.” From this, a tiered inclusion framework for secondary school chemistry is derived. This framework takes the philosophy of inclusive education as its fundamental starting point [3]. It reasonably deconstructs chemistry learning into two relatively independent dimensions: “classroom principle cognition” and “experimental operation verification.” The overall design concept is illustrated in Fig. 1.

Traditional chemistry experimental instruction relies heavily on the visual channel. Color-blind students face information-access barriers in both the classroom principle learning and experimental operation verification stages [2]. Research has shown that CVD students in teaching environments that depend on color to convey information often bear extraneous cognitive load induced by inappropriate instructional design [2]. Through the decoupling strategy, this study adopts symbolic representation at the theoretical level to replace the traditional reliance on macroscopic color, helping students construct internal mechanistic models of chemical reactions. At the practical level, digital tools are introduced according to differences in school resource conditions, enabling a shift from “qualitative observation” to “quantitative analysis.” This tiered system is unified under the core principle of inclusive education—“embracing diversity and serving all.” It aligns with the competency-oriented approach and quality-education goals currently advocated in secondary chemistry curriculum reform [4]. The aim is to provide flexible practical pathways for schools at different development stages within the context of resource disparity, ensuring that every student has equal opportunities for learning and development. This approach is consistent with the concept of “tiered empowerment” proposed in recent research [3]—that is, through scaffolded task design, all students can obtain learning experiences of varying degrees.

2.2. Symbolic Representation in Classroom Theory Instruction

This paper has carried out a clear and well-structured redesign of the explanatory model for acid–base indicators used in classroom teaching. It is first necessary to point out that the traditional textbook approach uses the macroscopic phenomenon of “solution color change” to explain ionization equilibrium shifts. This in essence adopts a single visual channel, and thereby naturally excludes CVD students [2]. From this, the fundamental principle of the Universal Design for Learning (UDL) framework is introduced: instructional materials should provide diversified means of information representation [5].

To this end, this paper employs geometry-based microscopic schematic diagrams (see Fig. 2). The acidic molecule (HIn) is depicted as a combination of a triangular prism and a three-dimensional sphere, where the three-dimensional sphere represents the proton. The basic ion (In^-) is depicted as a single triangular prism. In this way, the transformation of geometric shapes directly and clearly illustrates the proton transfer process. This approach aligns well with the “multiple representation” principle advocated in the UDL framework, thereby enabling color-blind students to construct the mental model of chemical equilibrium synchronously and fully alongside their peers with normal vision. More importantly, with the support of symbolic representation, students’ understanding of reaction mechanisms is no longer constrained by visual perception ability. The starting point of educational equity is therefore genuinely achieved [4].

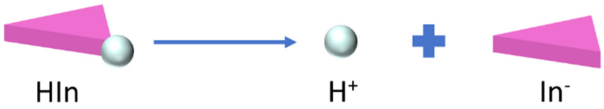

Fig 2. Microscopic schematic showing an acidic molecule losing a proton

2.3. Digital Support Pathways for Experimental Practice

This paper simultaneously presents a completely new design for the digital support pathway employed in the experimental operation component—that is, using digital means to compensate for the inadequacies of traditional visual colorimetric methods. Based on this, two flexible implementation plans are proposed. For resource-limited teaching environments (i.e., underdeveloped regions that lack sensor equipment), smartphone colorimetric applications can be used to allow students to photograph the reaction system and directly obtain RGB values. In this way, the originally subjective color judgment can be replaced by reliable, reproducible, and objective data [6]. Forming an excellent complement to this, for well-equipped modern laboratories, real-time pH sensors and digital projection systems can be used. Sensor probes collect reaction system data in real time, so that students can track the reaction progress completely and accurately without the need for visual color comparison. What is particularly noteworthy is that the proposed digital support pathway aligns well with the current research trend of AI-empowered chemistry experimental instruction [3]. The latter is also transforming traditional spectrographic analysis based on visual recognition into intelligent, automated data processing workflows. The two plans operate at different technological tiers, but their fundamental goal is the same: shifting from "qualitative observation" to "quantitative analysis." They therefore provide students with a truly diverse, inclusive, and flexible quality experience in experimental learning.

3. Results and Case Simulation

3.1. Analysis of the Teaching Effectiveness of Symbolic Representation

To verify the actual effectiveness of the symbolic strategy in theoretical instruction, this study conducted a visual differential comparison analysis on the commonly seen phenolphthalein color-change illustration in textbooks. The results are shown in Fig. 3.

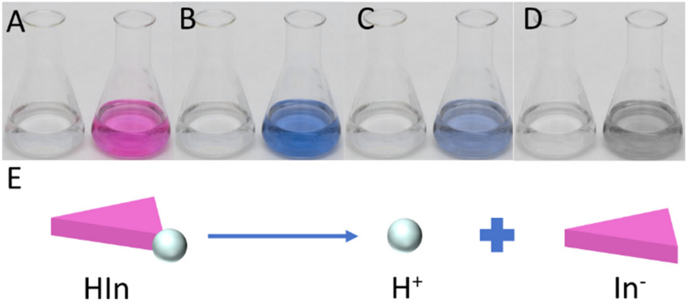

Fig 3. A: Phenolphthalein color change as seen by a person with normal color vision; B, C, D: Simulations for protanopia, deuteranopia, and total color blindness respectively; E: Redesigned phenolphthalein color-change mechanism, with the triangular prism representing the deprotonated chromophore

Fig. 3A shows the phenolphthalein color change observed by a person with normal color vision. The two colors of red and colorless form a clear and strong contrast. After processing with color blindness simulation filters, the images for protanopia (Fig. 3B), deuteranopia (Fig. 3C), and total color blindness (Fig. 3D) all lose their original color contrast. Specifically, both protanopia and deuteranopia cannot reliably distinguish the difference before and after the color change, and total color blindness simply cannot perceive any color change whatsoever. The traditional textbook practice of using color change during a reaction to explain the color-change mechanism is therefore essentially a concrete manifestation of "visual hegemony" in textbook design. It takes as its basic premise that all students possess normal color vision, and treats color change as a self-evident universal language. This implicitly erects an exclusionary barrier that, from the very beginning, shuts CVD students out of the process of meaning construction [2].

In the symbolic representation model proposed in this paper (Fig. 3E), the acidic molecule (HIn) is reasonably designed as a combination of a triangular prism and a sphere. The deprotonated chromophore (In^-) is represented as a triangular prism, and the proton is represented as a sphere. This clearly illustrates the process of proton transfer. More importantly, a systematic visual accessibility analysis clearly demonstrates the following: the traditional textbook illustrations (Fig. 3A–D) lose their color contrast under color blindness simulation, resulting in the loss of key information. In contrast, the shape-based reconstruction model (E) does not rely on color to convey information at all, and therefore retains 100% information fidelity for color-blind students. We believe that the designed symbolic strategy can effectively lower the learning barriers encountered by CVD students when studying chemical equilibrium, enabling all students to construct a mental model of chemical equilibrium. What is particularly noteworthy is that this design rigorously follows the fundamental principle of “providing multiple perceptual channels” proposed in the UDL framework [5]. It genuinely extends the communication of chemical concepts from a single color–visual channel to a shape–recognition channel.

3.2. Effectiveness of Digital Tools in Experimental Support

In the experimental operation component, this study analyzed the application effectiveness of the digital support pathways.

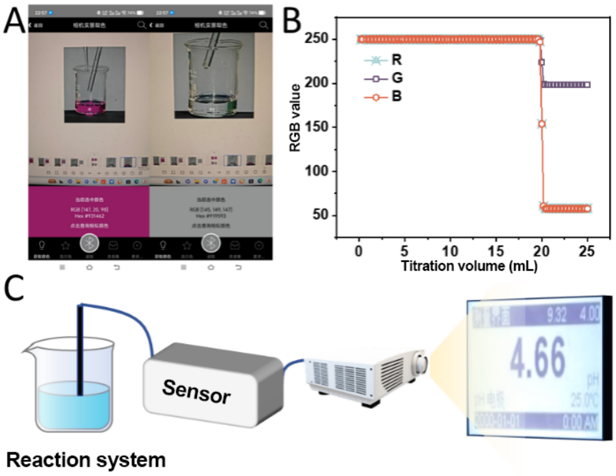

Fig 4. A: Image Color Picker real-time color extraction (taking the reaction of NaOH and HCl as an example); B: RGB value change curve; C: Real-time sensor detection and projection display

Starting from the acid–base titration experiment, the various shortcomings of the traditional method for determining the titration endpoint in experimental instruction can be illustrated. The traditional method uses indicator color change to determine the titration endpoint—that is, when phenolphthalein changes from colorless to pink, the endpoint is deemed to have been reached. However, this method of judgment has three very clear and important limitations. First, color change is subjective, as different people’s judgments of “pink” are not entirely the same. Second, the color transition zone near the endpoint is extremely difficult to discern, and the naked eye cannot easily observe it accurately. Third, color-blind students simply cannot obtain reliable information through this method [2].

Digital tools provide a viable pathway for solving this problem. Teachers in schools of economically underdeveloped regions can guide students to use smartphone colorimetric applications (such as Smart Color) to directly obtain the RGB values of the reaction system’s color changes and process the data (see Fig. 4A). This converts the originally subjective color perception into recordable, quantitatively analyzable, objective data [6]. Consequently, when the RGB values measured by the smartphone application exhibit a sharp, jump-like change over the course of the reaction time (see Fig. 4B), the reaction endpoint can be conveniently and reliably determined. Forming an excellent complement to this, school laboratories with adequate funding can employ real-time pH sensors and digital projection systems to carry out real-time monitoring and dynamic visualization of pH values during the reaction process (see Fig. 4C). This design provides critically important and substantive help to color-blind students: they no longer need to rely on difficult-to-discern color changes, and need only observe the data curve to determine the reaction progress.

4. Conclusion

Addressing the cognitive barriers encountered by CVD students in chemistry experiments, this paper has designed and constructed a “theory–practice decoupling” multi-tiered, multimodal instructional support system. It reasonably reconceptualizes chemistry learning along two independent dimensions: “classroom principle cognition” and “experimental operation verification.” Based on the foregoing discussion, we can draw the following conclusions.

(1) Symbolic representation effectively eliminates the sensory barriers encountered in theoretical learning. It can be seen from the simulation results that replacing traditional color changes with topological transformations of geometric shapes (triangular prisms, circles) can achieve high-fidelity information transmission under any color-vision modality. Therefore, constructing microscopic chemistry models without the use of color is feasible.

(2) Digital tools are conducive to achieving the objectification and universalization of experimental operations. They can—from smartphone colorimetric applications all the way to real-time sensor projection—transform the subjective “visual-qualitative” approach into an objective “data-quantitative” one. Moreover, the “frugal science” approach adopted by these digital tools uses highly ubiquitous mobile devices to bridge the “digital divide” among schools in different regions.

(3) We call for a re-examination of the positioning of traditional teaching tools. In the context of inclusive education, traditional color-change-based detection media such as pH paper should appropriately be repositioned from “measurement tools” to “conceptual demonstration aids.” Genuine quantitative analysis should therefore be appropriately delegated to digital tools. This kind of paradigm shift is both a concrete respect for student diversity and is consistent with the overall direction of modernization and data-driven transformation in chemistry education. In the future, this decoupling strategy can be naturally and appropriately extended to other visually dependent experiments such as precipitation reactions and flame tests, truly building a chemistry education environment for all.

References

[1] Z. Jia, H. Xing, Y. Li. Computational Chemistry Experiment on the Color-Change Mechanism of Phenolphthalein Indicator. University Chemistry. (2023), 2304074.

[2] Y.D. Jeong, J. Cho, Y. Son, et al. Global Prevalence of Congenital Color Vision Deficiency among Children and Adolescents, 1932–2022. Ophthalmology. Vol. 132 (2025) No. 12, p. 1431-1444.

[3] Information on: https://kns.cnki.net (AI-Empowered Chemistry Talent Cultivation Pathway: Construction of a Gas Chromatography Data Analysis Teaching Assistant System Based on an AI Innovation Education Platform, 2026-02-19).

[4] Information on: https://kns.cnki.net (Research on the Realistic Dilemma, Cognitive Basis, and Practical Strategies of Inclusive Education – From the Perspective of Otherness Theory, 2026-02-19).

[5] S.L. Moore. Differentiated Instruction in the Digital Age: Universal Design for Learning. Association for Supervision and Curriculum Development, 2002.

[6] Information on: https://kns.cnki.net (Visual Analysis of Acid–Base Reaction Titration Endpoint Determination Based on Smartphone APP, 2026-02-19).

[7] A.H. Johnstone. Teaching of Chemistry – Logical or Psychological? Chemistry Education Research and Practice. Vol. 1 (2000) No. 1, p. 9-15.