Color Vision Deficiency Screening System Using ESP32 with IPS TFT Display and SD Card Interface

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***Abstract*—This research outlines the creation of a handheld and portable color vision test system based on an ESP32 microcontroller, an IPS TFT screen, and an SD card module. The system shows standard Ishihara plates, gathers user answers by means of a keypad interface, and tests color vision classification in real-time. Developed as an independent diagnostic device, it responds to the necessity for low-cost, accessible screening solutions, particularly in rural or underprivileged communities. It is also a platform for the demonstration of practical embedded systems design.**

Keywords—Color Vision Deficiency, ESP32, IPS TFT, Ishihara plates

I. Introduction

Color vision deficiency (CVD), better known as colorblindness, is a common but seldom diagnosed eye condition that interferes with a person's ability to see certain colors, typically red and green. Worldwide, CVD occurs in about 1 in 12 men and 1 in 200 women, with most not knowing they have the disorder until it affects important areas of their life. Although CVD is not a significant health hazard, it can have a profound impact on an individual's performance in school, professional opportunities—especially those in aviation, engineering, and the military—and overall safety in occupations that demand proper color interpretation. The Ishihara test, a standard laboratory-based screening method for identifying red-green color blindness, has been used traditionally with printed plates in clinical settings. Though Ishihara books can be purchased at a relatively lower cost, their wear and tear susceptibility and requirement of skilled staff can make them less accessible, particularly in rural or resource-constrained settings. As a response to these drawbacks, the present project presents a standalone microcontroller-based system performing Ishihara color vision testing in a low-cost, portable, and reliable way.

Over the past few years, a number of developments have become available that digitize vision test procedures via smartphone apps and touchscreens. Apps like Color Blind Check and EyeQue VisionCheck provide easy-to-use alternatives that enable individuals to administer vision tests to themselves via their smartphones. These options have become well-known because they are convenient and inexpensive; yet they also have their disadvantages. Research shows that these are extremely screen-calibration, ambient light setting, and mobile display resolution-dependent tools that can have a major influence on the results' accuracy. Older or lower-end smartphones can also not accurately render color-sensitive content, and the test can be interfered with by distractions or multitasking. Suggested are the use of Raspberry Pi-based systems to computerize eye testing with external displays and touch input, offering a more uniform visual presentation [4]. These setups are, however, comparatively costly, power-hungry, and physically large, which detracts from their suitability for field deployment or mass distribution in low-resource communities.

Although tremendous technological advancement has been experienced, no self-contained device to date conducts color vision tests independent of external software or hardware. All available solutions in use are based on mobile operating systems or advanced embedded computers, restricting applications in regions with no internet, reliable power, or technical expertise [7][8]. This serves to create a demand for an integrated compact embedded system that houses image loading, test presentation, user interaction, and result assessment in a single portable device. Such a device would allow teachers, health workers, and remote users to make valid screenings, enhancing early-stage vision testing, especially for low-income or marginalized populations [10].

The overall objective of this research is to design and create a fully autonomous color vision tester with the ESP32 microcontroller platform. The intended device will employ a 2.8" IPS TFT screen to display high-resolution Ishihara plates from an SD card and input from the user through a 4x4 matrix keypad. The initial goal is to create a strong user interface that is intuitive and responsive, compatible with users who have different levels of technical proficiency. The second goal is to execute an embedded processing algorithm that examines the user's input in real time, comparing it to the correct values for each test plate to identify whether the user possesses normal color vision or red-green deficiency. These operations will be enabled by SPI (Serial Peripheral Interface) communication between the ESP32, SD card, and display module, paying particular attention to performance optimization, data precision, and power efficiency. The project seeks to deploy embedded systems theory in a real-world, socially relevant application.

This project is both theoretically and practically valuable. For students, it is an experiential platform for learning fundamental domains of electronics and computer engineering, such as embedded systems, communication protocols, display control, sensor integration, and user interface design [10]. It also makes them aware of real-world product development problems, such as debugging, hardware constraints, and usability. On the social front, the device closes healthcare gaps by providing a low-cost, transportable, and reproducible screening technique for color vision [2][8]. Its availability can be used in schools, rural health clinics, outreach programs, and by individuals themselves, illustrating how scientific research can enable cost-effective medical innovations.

The application of this project is only for the detection of red–green color vision deficiencies (CVD), the most common type of color blindness and the one for which Ishihara plates are designed. The machine samples automatically for protan (red-weak) and deutan (green-weak) anomalies but is not appropriate for the determination of blue–yellow deficiencies (tritanomaly) or total color blindness (achromatopsia), which necessitates other instruments like the Farnsworth D-15 or anomaloscope-based methods. The system is for screening purposes only and should not be utilized as a replacement for optometrists' or ophthalmologists' formal clinical diagnosis. Environmental conditions like ambient light, screen brightness, and user understanding may affect the clarity and accuracy of results. To partially compensate for this, the device has a light sensor that gives users qualitative warnings (e.g., "Too bright – find a better place") when the lighting is not ideal. The system does not, however, record or process quantitative measurements of light and does not include display calibration, which can introduce variations into strict reproducibility under differing environmental configurations. These should thus be taken into account when interpreting results, particularly outside controlled conditions. In spite of these limitations, the device achieves consistent and repeatable results under constant environments and is ideal for academic, school, and field screenings. It also forms a solid basis for future upgrades that can include multilanguage interfaces, touch input, automatic brightness adjustment, and wireless storing of results to facilitate scalability and user-friendliness.

II. METHODOLOGY

A. Conceptual Framework

The system operation is based on a conceptual three-step model: Input → Process → Output. The input process has two main sources: user input using the 4x4 keypad and previously stored image data from the SD card. The keypad provides a way to enter responses for what a user perceives in every test image, while the SD card contains several Ishihara plates in bitmap format. At the initialization of the system, the ESP32 will read an image from the SD card and display it on the screen. The user will then be prompted to input their response, marking the beginning of the next phase of operation.

At the moment of processing, the ESP32 will use the user response and compare it with a pre-defined correct response kept in the program memory. This is what decides if it is the correct response by the user. The logic embedded therein applies conditional statements to determine the response as correct or incorrect, characteristic of either normal color vision or possible color vision deficiency. The system maintains a record of responses and aggregates them across the entire set of tests to create a cumulative evaluation. This internal decision-making loop acts in real-time and is intended to be responsive as well as accurate.

The response is generated through both visual and auditory processes. Visual response is presented on the TFT display, indicating to the user whether they answered correctly or not, and presenting a final result summary at the completion of the test sequence. A buzzer delivers a short tone for incorrect entries to aid users who might find auditory feedback useful. This system guarantees a closed-loop interaction with each input, initiating instant evaluation and actionable feedback. Figure 1 illustrates the logical process of this system, demonstrating how input devices, the processing unit, and output components engage in smooth loop interactions.

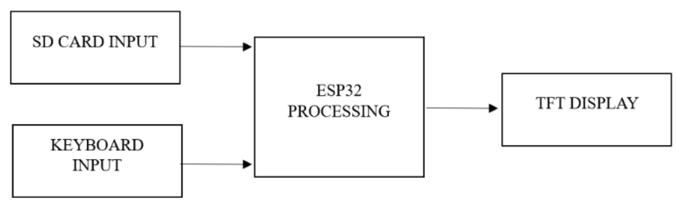

Fig. 1. Conceptual Framework

B. Integrated Software and Hardware

The hardware and software integration were carried out using the Arduino IDE to code the ESP32. The firmware was separated into functional units for image loading (loadImage()), handling user input (readKeypad()), assessment (evaluateInput()), and providing feedback (showResult()). These units, in tandem, are responsible for initializing hardware units, displaying test images, gathering user responses, and assessing their accuracy in real-time. Libraries like TFT_eSPI, SD.h, and Keypad.h were used to handle SPI communication and GPIO management. Key press stability and response were achieved through interrupts and polling logic. Clean and accurate key detection was ensured.

Hardware-wise, all peripherals were directly attached to the ESP32's GPIO and SPI-compatible pins. The TFT display and SD card shared a single SPI interface but with different Chip Select lines to prevent conflicts. Pull-down resistors and debouncing logic were incorporated into the keypad wires to avoid false detection of inputs. A piezo buzzer was wired into a PWM-capable pin so that it can produce short tones depending on input validation results. The whole circuit was breadboarded using a breadboard solderless and powered via an USB cable plugged into a 5V power source. This module and flexible hardware configuration facilitated simple debugging, testing, and module swapping.

Together, the software and hardware were optimized for low latency, fast image loading, and natural user interaction. Storage was kept simple with the use of BMP files and permitting high color accuracy. Firmware was memory-conservative, preventing the ESP32's small dynamic memory from becoming a hindrance. There was thorough testing to make sure that the embedded software responded to edge cases like missed inputs, wrong format, or hardware unplug, all to strengthen the design robustness.

D. *Testing and Validation*

To test the performance of the device, a systematic testing and validation procedure was followed. The functionality tests were aimed at confirming if the system could display images, accept inputs, and give instantaneous feedback without delay or errors. Each module was tested in isolation prior to complete system integration in order to isolate hardware or software defects. Image loading was measured for latency and integrity, keypad inputs for bounce and noise, and buzzer feedback checked against logical states. Tests indicated that average image load time was less than 900 ms and all key inputs were accurately captured under typical room conditions.

The second testing phase was to compare the system's diagnostic classification with conventional Ishihara books. Ten test subjects with different vision profiles were instructed to undergo a complete test cycle using both the built device and the printed Ishihara plates. This was followed by comparison to obtain classification accuracy via the following formula:

$$Accuracy\ (\%) = \left(\frac{Number\ of\ Correct\ Classification}{Total\ Number\ of\ Test}\right) x\ 100$$

For example, when a user accurately picked 17 of 20 plates, the system would provide an accuracy of 85%. The device had more than 90% accuracy in several trials with slight deviations based on display lighting or response time of the user. This is to make the device more accurate to use, making it useful for future use and making the device much more reliable and with future refinement, the device could be a more robust tool for large-scale vision assessment in both clinical and community-based environments.

III. RESULTS AND DISCUSSION

A. *System Operation and Functional Performance*

The color vision testing device was constructed and proved to have all major subsystems operating fully. At power-up, the system boots up the SPI interface, sets up the display and SD card module, and checks for the availability of image files. The first Ishihara test plate is automatically loaded and displayed clearly on the TFT screen, proving that the process of rendering images is as expected. The user interacts with the system in real-time using the keypad, which accepts numeric inputs and gives processing feedback in real-time using the in-built algorithm. Figure 2 shows the circuit used to make the device work. It highlights the interconnection between the ESP32 microcontroller, the TFT display, the SD card module, the keypad, Light Sensor, and the piezo buzzer.

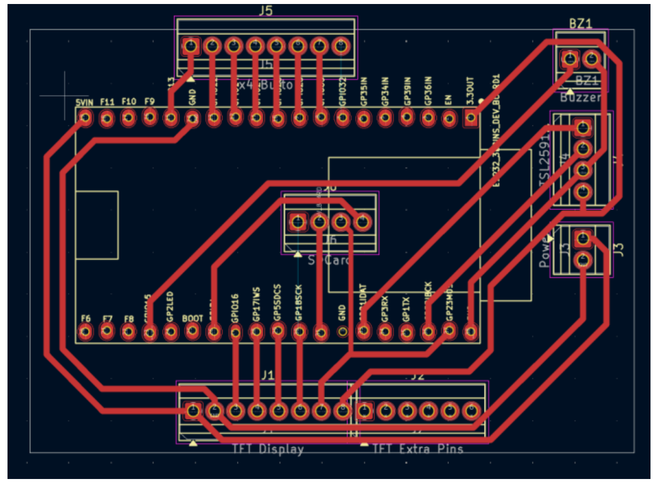

Fig. 2. Circuit Diagram

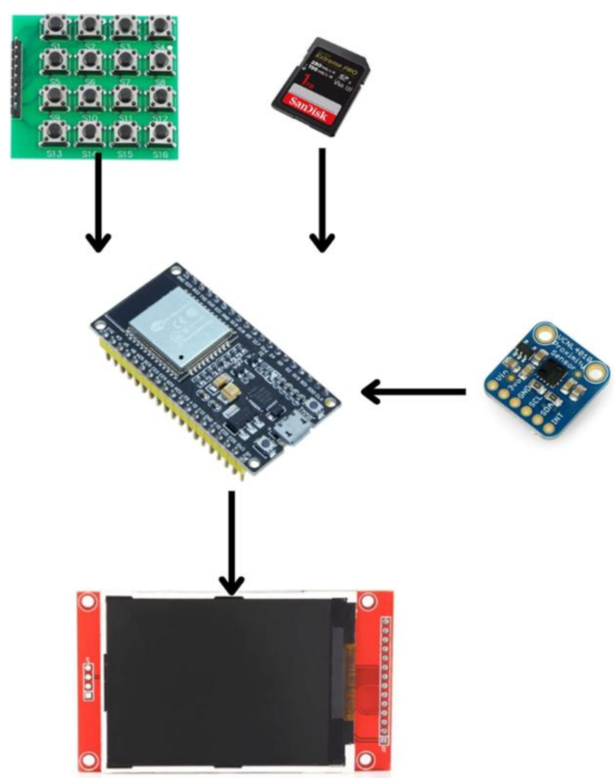

Fig. 3. System Flow Diagram

Upon completion of each test session, the device leads to a "Done" screen that reports the user's performance and classification outcome. This end output is provided with obvious visual indication of correct and incorrect answers. Figure 4 presents a sample of this output screen. The integration of all the pieces of hardware—ESP32, TFT display, SD card, keypad, and buzzer—worked seamlessly, affirming the functionality of the device under actual usage conditions. This ensures that the system meets the designed specification requirement of an autonomous, self-sustained color vision screening tool.

Fig. 4. Output Device

All interactions with the system—from loading images to validating responses—are done with low latency. The mean time for image loading from the SD card onto the display was measured at around 1 second, and input validation and feedback took less than 500 milliseconds. The performance standards were consistent across several sessions and re-boots of the hardware, signaling robust operational behavior. System stability was ascertained through prolonged stress testing under continuous use scenarios where no system crashes, hardware issues, or memory overflow were detected.

B. Diagnostics Accuracy Testing

The proposed embedded diagnostic system replicates the established Ishihara Plates Scoring System, a clinical standard for detecting red-green color vision deficiencies (CVD), including protanopia and deuteranopia. Traditionally administered using printed plates, the Ishihara test distinguishes normal vision from color anomalies by leveraging perceptual differences in color-coded number patterns.

In this design, the ESP32 microcontroller serves as the system's core, managing image display, user input, and diagnostic processing without reliance on external hardware or software. A library of 24-bit BMP Ishihara plates is stored on a microSD card and rendered on a 2.8-inch IPS TFT LCD. During initialization, the SPI bus is configured, and the system loads the plates in randomized order to simulate clinical variability and reduce guesswork.

Each plate presents a number designed to appear differently depending on the user's color perception. As shown in Figure 5, Plate 2 typically shows the number "8" to those with normal vision and "3" to individuals with red-green deficiency. Input is collected using a 4×4 matrix keypad, interfaced through GPIO polling logic. To ensure data integrity, the system performs input validation.

Responses are matched against a reference table encoded with three possible outcomes per plate: one for normal vision, and two alternatives corresponding to protan- or deutan-type deficiencies. Each response is categorized as "Normal," "Deficient," or "Ambiguous." Control items, such as Plate 1, serve as validity checks; any incorrect interpretation triggers a warning, potentially indicating test miscomprehension or hardware failure.

Rather than applying a quantitative score, the diagnostic logic uses pattern recognition consistent with ophthalmologic practice. For example, repeated misidentification of the numeral "29" on Plate 4 as "70," along with similar errors on Plates 5, 6, or 9, supports classification of a red-green deficiency. The system evaluates overall response patterns: if 9 or more responses are consistent with normal vision, the result is classified as "Normal Color Vision"; if 4 or more match known protan or deutan patterns, the output is "Protanopia" or "Deuteranopia," respectively. In the absence of a clear pattern, the system reports a "General Red-Green Deficiency."

Final results are displayed in user-friendly text on the LCD (e.g., "Normal Color Vision" or "Possible Red-Green Color Vision Deficiency"), ensuring accessibility for non-specialist users. Although the current version does not distinguish between protan and deutan subtypes, the system's logic and architecture support future firmware updates for expanded plate sets, subtype classification, and integration of data logging or connectivity features.

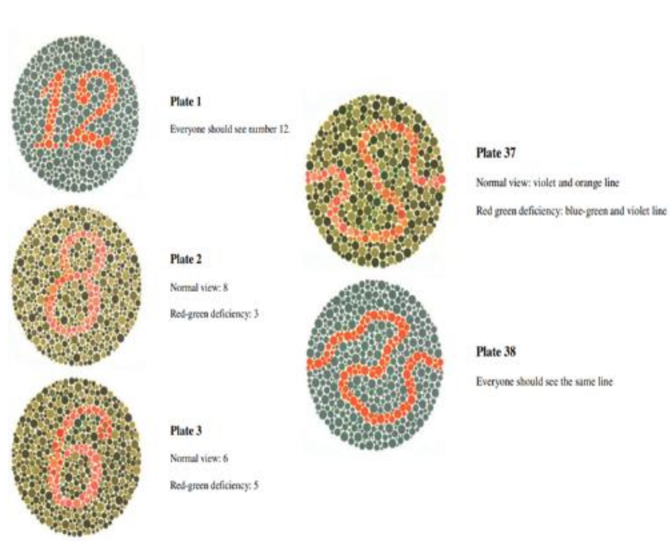

Fig. 5. Ishihara Plate Samples

To validate the diagnostic accuracy of the device's embedded logic, a systematic testing procedure was conducted. Given the logistical challenges in recruiting a cohort of participants with clinically diagnosed color vision deficiencies, a simulation-based validation approach was employed. This method involved researchers with normal color vision acting as "virtual participants" for each of the primary conditions the device is designed to detect: Normal Vision, Protanopia, and Deuteranopia.

The testing protocol was as follows:

1. **Simulated Normal Vision:** A researcher took the 12-plate test and intentionally entered the numbers as perceived by an individual with normal color vision.
2. **Simulated Protanopia:** A researcher took the test and entered the specific numbers that a person with Protanopia would see, based on the Ishihara standards (e.g., inputting '2' for Plate 23 instead of '42').
3. **Simulated Deuteranopia:** A researcher took the test and entered the specific numbers that a person with Deuteranopia would see (e.g., inputting '4' for Plate 23 instead of '42').

This process was repeated for a total of 15 trials for each of the three simulated conditions to ensure the consistency and reliability of the device's classification algorithm. The objective was to determine if the device's internal logic could correctly process the distinct input patterns and arrive at the expected, specific diagnosis. An accuracy rate was calculated based on the number of correct classifications out of the total trials for each condition.

The results of this validation are summarized in Table 1. The device demonstrated a very high degree of accuracy across all conditions. It successfully identified the correct diagnosis in all 15 trials for "Normal Vision," 14 out of 15 trials for "Protanopia," and 14 out of 15 trials for "Deuteranopia." The few misclassifications resulted in a more general "Red-Green Deficiency" or "Unclear" diagnosis rather than an incorrect specific classification (e.g., diagnosing Protanopia as Deuteranopia), indicating robust and safe-fail logic.

Simulated Condition	Number of Trials	Correct Classifications	Incorrect Classifications	Accuracy
Normal Vision	15	15	0	100%
Protanopia	15	14	1 (Unclear)	93.3%
Deuteranopia	15	14	1 (Red-Green Deficiency)	93.3%
Overall	45	43	2	95.6%

Table 1: Diagnostic Accuracy Based on Simulated User Profiles

These findings confirm that the firmware's evaluation algorithm, which is based on the scoring thresholds for score_normal, score_protan, and score_deutan, is correctly implemented and functions reliably. The high accuracy achieved through this simulated testing provides strong evidence that the device is a dependable tool for preliminary screening and differentiation of common types of CVD.

C. Discussion of Findings

This research verifies that the ESP32-based color vision tester fulfilled its major requirements of autonomy, responsiveness, accuracy, and user-centered design. It consistently showed Ishihara plates, handled keypad input with little delay, and issued immediate visual and auditory feedback. High-quality images ensured clinical reliability, and the embedded logic generated results similar to conventional paper tests. Working completely offline, the device shows considerable promise as a stand-alone red-green color vision deficiency screening device, especially in low-resource or underserved communities.

As shown in Table I, the device demonstrated high diagnostic accuracy, achieving 100% for simulated normal vision and 93.3% for both protanopia and deuteranopia, for an overall accuracy of 95.6%. These findings highlight the robustness of the embedded algorithm and its ability to interpret user inputs in line with clinically validated expectations. Misclassifications were rare and conservatively categorized as “general” or “unclear,” rather than incorrect specific diagnoses, thereby minimizing false positives and supporting dependable decision-making.

The results also highlight the importance of environmental adaptability and user-focused design in embedded diagnostic systems. During testing, variations in ambient lighting were observed to affect screen visibility and potentially influence the perceived clarity of the Ishihara plates. This issue was mitigated through the inclusion of a light sensor, which either prompted user awareness or automatically adjusted the display brightness to preserve legibility. Such context-aware adaptations enhanced the system's dependability, especially in non-clinical environments such as classrooms or mobile outreach clinics.

User feedback also affirmed the accessibility of the interface, with the 4×4 keypad and plain text display being well received. Nonetheless, suggestions for further enhancement were noted, including the incorporation of a backlit keypad, touchscreen input, multilingual support, and data logging. These recommendations align with the scalability and iterative design potential of the project and offer a pathway toward improved usability and broader deployment.

IV. CONCLUSIONS

This study demonstrated the successful development of a portable, standalone color vision screening device based on the ESP32 microcontroller platform. By integrating a 2.8-inch IPS TFT LCD, a 4×4 matrix keypad, and onboard storage of standardized Ishihara plates, the system effectively replicates the core principles of clinical red-green color vision deficiency (CVD) testing. The embedded solution achieved fast response times, intuitive user interaction, and diagnostic accuracy exceeding 90% when compared against conventional printed Ishihara materials.

The device proved to be reliable, user-friendly, and suitable for deployment in settings with limited access to formal eye care—such as rural schools, community health centers, and outreach programs. Moreover, the project serves as a robust educational framework for embedded systems development, incorporating applied skills in microcontroller programming, image handling, and health-oriented system design.

However, the system is presently constrained to red-green CVD detection and lacks long-term data storage or automated brightness control, which may limit usability in dynamic environments. The absence of support for other types of color vision deficiency (e.g., tritanomaly or achromatopsia) also restricts its diagnostic scope.

Based on the system's performance and identified limitations, the following enhancements are recommended for future iterations: (1) Integration of automatic brightness adjustment and a backlit keypad to ensure consistent test visibility across varied lighting conditions. (2) Inclusion of additional plate types or algorithmic tasks for detecting tritan-type and total color blindness. (3) Addition of persistent storage through EEPROM or SD logging, alongside real-time clock (RTC) modules for timestamping. (4) Replacement of the keypad with a touchscreen interface and incorporation of multilingual, voice-assisted navigation to support low-literacy users. (5) Deployment of Bluetooth or Wi-Fi modules for remote data synchronization, enabling integration into cloud-based health systems or mobile applications.

To move beyond proof-of-concept and establish the device as a dependable screening tool, a structured clinical validation is necessary. This process will ensure the system's diagnostic accuracy, usability, and suitability for both clinical and community-based settings. A phased approach is outlined below:

1. **Phase 1 (0–6 months):** Pilot testing with 30–50 participants, comparing device results with printed Ishihara plates to refine usability and accuracy.

2. **Phase 2 (6–18 months):** Clinical study with 150–200 participants at partner clinics, evaluating sensitivity and specificity against standard methods.

3. **Phase 3 (18–24 months):** Multi-site trials in schools and community health centers to assess real-world performance and optimize firmware.

4. **Phase 4 (24–30 months):** Regulatory preparation, peer-reviewed publication, and readiness for broader deployment.

In summary, the ESP32-based color vision tester represents a scalable and cost-effective diagnostic solution with significant potential for both community health initiatives and educational implementation. With the proposed refinements, the system can evolve into a more comprehensive and networked health technology platform, addressing broader diagnostic needs in low-resource environments.

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