

Reaction Time Measurement and Training Device

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1. Introduction

1.1 Problem

Reaction time is important in sports, gaming, driving, and rehabilitation. Phone and computer tests are convenient, but their results include delays from display refresh rates, operating-system scheduling, and touchscreen input, making it difficult to separate true reaction time from device latency.

Dedicated reaction-training systems reduce these errors but often cost several hundred dollars, which is not feasible for the casual user. Our goal is to build a lower-cost standalone device using physical lights and buttons, with stimulus and response signals exposed at test points so timing can be verified directly with an oscilloscope or logic analyzer.

Instead of generating the waiting period entirely in software, the device uses a motor-driven encoder. A rotating disk determines when the stimulus is triggered, making the delay dependent on physical motion while also adding motor control, encoder sensing, and mechanical integration to the design. This prevents the user from learning any software tendencies or patterns.

The device is intended for training and measurement, not medical use. Its main benefit is an affordable reaction-time system with timing that can be independently verified.

1.2 Solution

The proposed device is a standalone reaction-time trainer consisting of a 3×3 grid of illuminated pushbuttons, a motor-driven optical encoder, an OLED display, a piezo buzzer, and a custom PCB based on an ESP32-WROOM-32E. A DC gearmotor continuously rotates a two-track encoder disk. One track provides regular pulses for monitoring motor speed, while the second provides one index pulse per revolution. When a trial begins, the ESP32 ignores the next index pulse and triggers the stimulus on the following pulse. At a target speed of 30 rpm, this produces a mechanically determined delay between approximately 1.9 and 4.3 seconds.

After the trigger, the ESP32 activates one of the nine LEDs or the buzzer and measures the time until the corresponding button is pressed using hardware timing. Debounce logic rejects additional switch transitions so that each press produces one measurement. The ESP32 then displays the result and can transmit it over Bluetooth only after the measurement is complete, preventing communication delays from affecting the recorded time. Test points on the stimulus and conditioned button signals allow the measured reaction time to be independently verified with an oscilloscope or logic analyzer.

1.3 Visual Aid

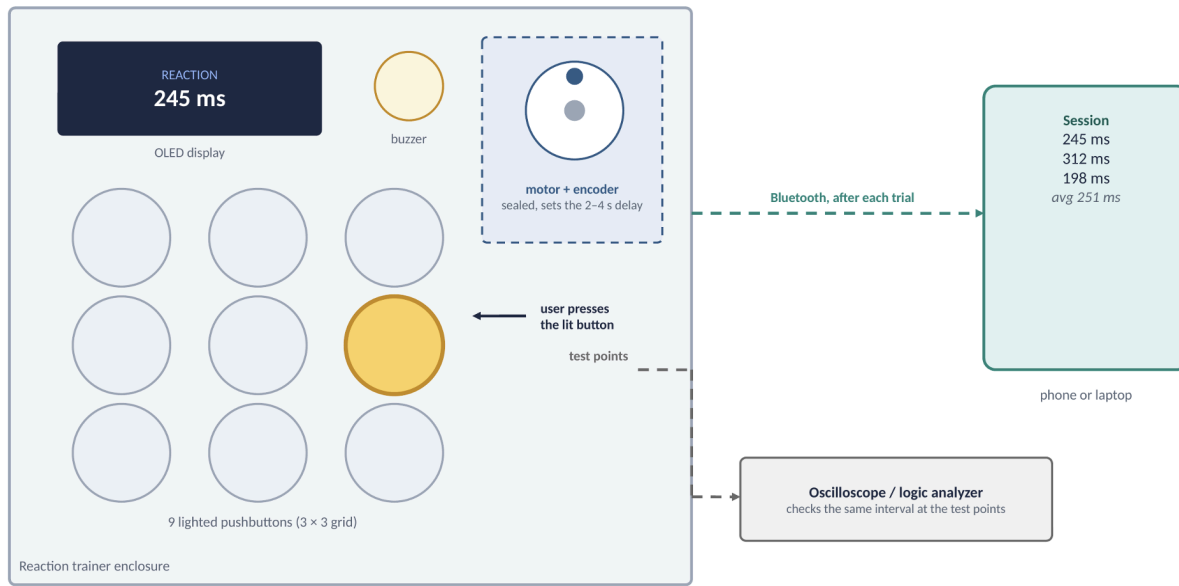


Figure 1. The device in use. The motor driven encoder inside the sealed enclosure decides when the stimulus happens. The user presses the lit button, the reaction time appears on the OLED, and the finished result is sent over Bluetooth to a phone or laptop. Test points let an oscilloscope measure the same interval.

1.4 High-Level Requirements

1. The stimulus delay shall be produced by the physical rotation of the motor driven encoder, shall fall between 1.9 s and 4.3 s, and shall produce exactly one valid stimulus trigger in at least 95% of armed trials.
2. The device shall measure the time between the electrical stimulus edge and a valid button response with a resolution of 1 ms or better, and this measurement shall agree with an oscilloscope or logic analyzer reading to within ± 2 ms in at least 95% of valid trials.
3. The device shall support all nine visual stimulus positions and the audio stimulus and shall successfully complete and store at least 95 out of 100 reaction-time trials with Bluetooth disconnected.

2. Design

2.1 Block Diagram

The system has six subsystems: control and timing, electromechanical delay, response, stimulus, and display and wireless, all fed by the power subsystem. The ESP32-WROOM-32E sits in the middle and every other subsystem connects to it. Figure 2 shows the connections, the supply rails, and the data protocol on each interface.

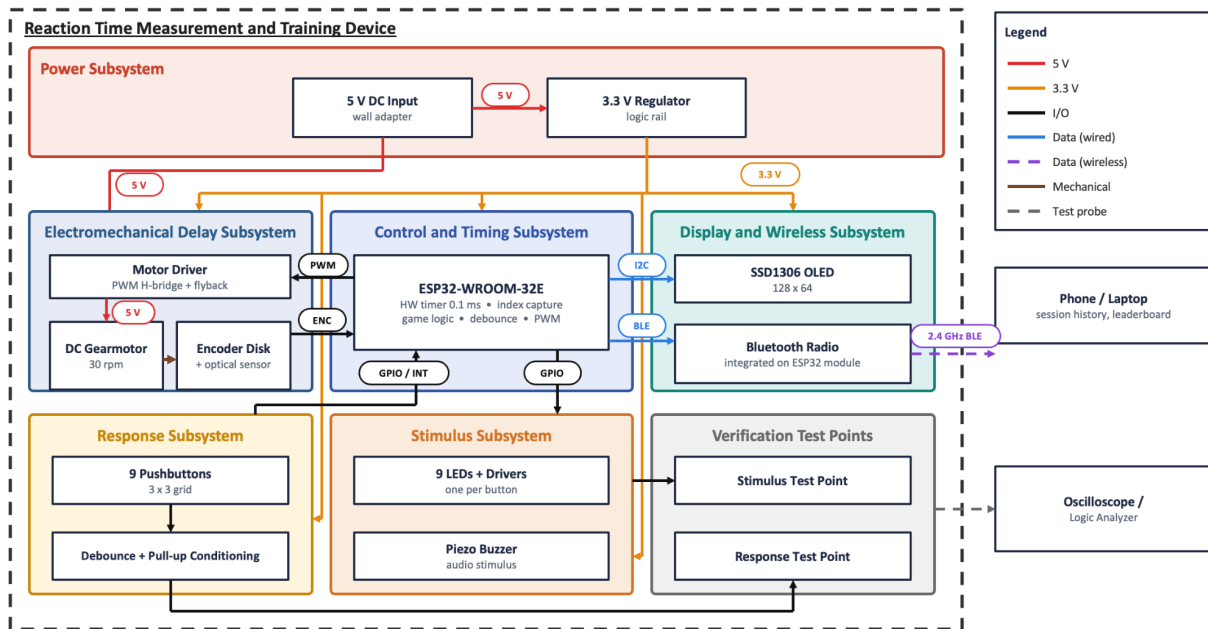


Figure 2. System block diagram. Red lines are 5V, orange lines are 3.3V, black lines are digital I/O, blue lines are wired data, purple is wireless data, and dashed lines denote wireless or test connections. The 5 V input is regulated to a 3.3 V logic rail, and the motor runs from a separate 5 V branch that shares ground with the logic.

2.2 Timing and Control Subsystem

The timing and control subsystem coordinates the entire device. The ESP32 reads the encoder speed and index signals, commands the motor driver through PWM, selects and activates the stimulus, detects button responses, measures reaction time, updates the display, and sends completed results over Bluetooth. Digital signals exchanged with the encoder, response, and stimulus subsystems use 0–3.3 V logic. This subsystem supports all three high-level requirements by coordinating the mechanically generated stimulus delay, performing the reaction-time measurement, and managing standalone system operation.

Timing-critical events are handled using interrupts and a free-running hardware timer rather than software delays or main-loop polling. The stimulus and response edges are timestamped from the same timer so

their difference directly represents reaction time. Display updates and Bluetooth communication occur only after the response timestamp has been recorded.

Requirements

1. The reaction-time timer shall have a resolution of 0.1 ms or better and shall measure intervals of at least 5 s without rollover.
2. Stimulus and response events shall be timestamped using the same free-running hardware timer through interrupt-based event handling rather than main-loop polling.
3. The controller shall independently identify all nine button inputs, the encoder speed signal, and the encoder index signal.
4. A valid response received before the stimulus event shall cancel the active trial and mark it as a false start.
5. Display updates and Bluetooth transmission shall not begin until both the stimulus and response timestamps for the active trial have been recorded.
6. The controller shall complete at least 100 consecutive valid reaction-time trials without a reset, missed timestamp, or corrupted stored result.

2.3 Electromechanical Delay Subsystem

The electromechanical delay subsystem generates the waiting period before each stimulus using physical motion. A DC gearmotor rotates an optical encoder disk containing a repeating speed track and a separate index track. The speed track provides feedback to the timing and control subsystem, which regulates motor speed using a PWM control signal to the motor driver. The index track provides one digital index event per revolution. This subsystem directly supports the first high-level requirement by generating the stimulus delay from physical motor and encoder motion rather than from a software-generated random delay.

The target motor speed is 30 rpm. When a trial is armed, the first valid index pulse is ignored and the following index pulse initiates the stimulus. Because the disk may be at any angular position when the trial begins, the resulting delay varies naturally from trial to trial. The motor, shaft, and encoder disk are enclosed to prevent physical contact and to keep the user from observing the encoder position and anticipating the stimulus.

Requirements

1. The closed-loop motor controller shall maintain an average rotational speed of 30 rpm within $\pm 5\%$ during a 60 s continuous run.
2. The encoder shall produce at least one speed-feedback pulse per revolution and exactly one distinguishable index pulse per revolution.
3. Encoder outputs delivered to the timing and control subsystem shall remain within the 0–3.3 V digital logic range.
4. The stimulus shall be initiated by the second valid index pulse following the arming event rather than by a software timing delay.

5. The measured delay from arming to stimulus shall fall between 1.9 s and 4.3 s during normal operation.
6. At least 95 of 100 armed trials shall produce exactly one valid stimulus trigger.
7. If no valid index pulse is detected within 2.5 s of the expected index event, the active trial shall be cancelled and marked invalid rather than triggering a stimulus through software.
8. The motor drive circuit shall include transient suppression sufficient to keep the motor driver and connected circuitry within their rated voltage limits.

2.4 Response Subsystem

The response subsystem consists of nine mechanical pushbuttons corresponding to the nine visual stimulus positions. Each button is independently connected to the timing and control subsystem through a pull-up and signal-conditioning circuit. The conditioned output is a 0–3.3 V digital signal that is sent simultaneously to the controller and an external test point. This subsystem directly supports the second high-level requirement by generating the electrical response edge used for both the internal reaction-time measurement and external oscilloscope verification.

Mechanical switches can produce multiple electrical transitions during a single press. The first valid conditioned edge after the stimulus is therefore treated as the reaction event, while subsequent transitions are ignored during a debounce interval. Because the controller and external test point receive the same conditioned signal, the externally measured response edge can be directly compared with the timestamp used by the device.

Requirements

1. All nine buttons shall be detected independently, and activation of one button shall not register as activation of another button.
2. One physical button press shall produce no more than one valid response event.
3. The first valid conditioned button edge following the stimulus shall define the response timestamp.
4. The signal-conditioning circuit shall introduce less than 1 ms of delay between the raw switch transition and the conditioned output.
5. Additional transitions from the same button shall be ignored for at least 20 ms after the first valid response edge.
6. The conditioned response signal supplied to the controller shall remain between 0 V and 3.3 V during all press and release conditions.
7. The conditioned response signal shall be accessible at an external test point without opening the enclosure.

2.5 Stimulus Subsystem

The stimulus subsystem provides both visual and audio reaction cues. Nine individually controlled LEDs correspond to the nine pushbutton positions, while a piezo buzzer provides the audio stimulus. The timing

and control subsystem provides the selected stimulus command, and the electrical stimulus-control signal is simultaneously routed to an external test point. This test-point transition defines the beginning of the interval used for external timing verification. The subsystem supports the second high-level requirement by providing a measurable timing reference and the third high-level requirement by providing all nine visual stimuli and the audio stimulus.

Each LED includes current-limiting circuitry, and driver circuitry is used where necessary so the controller does not directly supply excessive load current.

Requirements

1. Each of the nine visual stimulus positions shall be controlled independently.
2. A visual trial shall activate exactly one of the nine selected LEDs.
3. Each active LED shall operate at a current between 12 mA and 18 mA.
4. The electrical stimulus signal shall change state within 0.5 ms of the accepted encoder trigger.
5. The electrical stimulus signal shall be accessible at an external test point without opening the enclosure.
6. The audio stimulus shall produce a sound-pressure level between 60 dBA and 85 dBA measured at a distance of 0.5 m.

2.6 Display and Wireless Subsystem

The display and wireless subsystem presents completed measurements to the user and optionally transmits them to an external device. An OLED connected to the timing and control subsystem through an I²C interface displays device status, test mode, and reaction time. Bluetooth transfers completed trial records to a paired phone or computer for session history or leaderboard functions. This subsystem supports the third high-level requirement by providing local operation while allowing optional wireless logging.

Wireless communication is not part of the timing path. Transmission begins only after the reaction-time measurement has been stored, ensuring that Bluetooth latency or disconnection cannot affect the measured value or prevent standalone operation.

Requirements

1. The display shall show the completed reaction time with 1 ms resolution within 200 ms of the end of a valid trial.
2. The display shall provide distinguishable indications for at least four system states: ready, armed, result, and error.
3. Each transmitted trial record shall contain a session identifier, reaction time, and trial type.
4. At a separation of 3 m, at least 95 of 100 transmitted records shall arrive at the paired host with values identical to the locally stored records.
5. With Bluetooth disconnected, the device shall successfully complete and locally display at least 95 of 100 otherwise valid reaction-time trials.
6. Loss of the Bluetooth connection during or between trials shall not erase or modify a reaction-time measurement that has already been recorded.

2.7 Power Subsystem

The power subsystem supplies stable power to every electrical subsystem. The device accepts an external 5 V DC input. The motor driver operates from the 5 V branch, while a regulated 3.3 V rail supplies the controller and low-voltage logic circuitry. Bulk capacitance on the motor branch and local decoupling near digital circuitry reduce disturbances caused by motor startup and switching. This subsystem supports all three high-level requirements by ensuring that motor operation does not disrupt stimulus generation, reaction-time measurement, or standalone system operation.

The power subsystem interfaces with the electromechanical subsystem through the 5 V motor branch and with the remaining low-voltage circuitry through the regulated 3.3 V rail.

Requirements

1. The device shall operate from an external DC input of 5 V $\pm 5\%$.
2. The regulated 3.3 V rail shall remain between 3.135 V and 3.465 V during normal operation, including motor startup and stall conditions.
3. The power supply and regulator shall support the measured worst-case simultaneous system current with at least 25% current margin.
4. Motor operation shall not cause the regulated 3.3 V rail to leave the range of 3.135 V to 3.465 V.
5. Motor startup, continuous operation, and shutdown shall not cause the controller to reset or corrupt an active or stored reaction-time measurement.
6. The device shall operate continuously for at least 60 minutes with the motor running without a controller reset or loss of stored trial data.
7. The motor supply branch shall include transient suppression sufficient to keep all connected components within their rated voltage limits.

2.8 Tolerance Analysis

The electromechanical delay subsystem is the highest-risk block in the design because it combines closed-loop motor control, optical sensing, and moving components, and it determines when each stimulus occurs. If the subsystem fails to generate the correct index event, high-level requirement 1 cannot be satisfied. The following analysis shows that the required stimulus-delay range remains achievable even at the maximum allowable motor-speed error.

At the target motor speed of 30 rpm, one revolution requires

$$T_{\text{rev}} = 60 / N = 60 / 30 = 2.00 \text{ s} \quad (1)$$

When a trial is armed, let t_1 be the time until the next index pulse. Because the disk is already rotating and may be at any angular position when the trial begins,

$$0 < t_1 \leq T_{\text{rev}} = 2.00 \text{ s} \quad (2)$$

The first index pulse is ignored and the stimulus is triggered by the following index pulse. Therefore,

$$t_{\text{delay}} = t_1 + T_{\text{rev}}$$

which gives

$$2.00 \text{ s} < t_{\text{delay}} \leq 4.00 \text{ s} \quad (3)$$

at exactly 30 rpm.

The closed-loop motor requirement allows a speed error of $\pm 5\%$, giving a speed range of 28.5 to 31.5 rpm. The corresponding revolution periods are

$$T_{\text{rev,min}} = 60 / 31.5 = 1.905 \text{ s}$$

and

$$T_{\text{rev,max}} = 60 / 28.5 = 2.105 \text{ s}.$$

The worst-case stimulus-delay range is therefore approximately

$$1.905 \text{ s} < t_{\text{delay}} \leq 4.211 \text{ s}.$$

Thus, maintaining the motor speed within $\pm 5\%$ is sufficient to satisfy the subsystem target of approximately 1.9 to 4.3 s without requiring tighter speed regulation.

The motor determines when the stimulus occurs but does not determine the accuracy of the reaction-time measurement itself. Reaction time is measured from the electrical stimulus edge to the accepted button-response edge using the same hardware timer. A timer resolution of 0.1 ms is ten times finer than the required 1 ms reported resolution.

The complete timing path will be verified by simultaneously probing the stimulus and conditioned-response test points with an oscilloscope or logic analyzer. If t_{ESP32} is the interval reported by the device and t_{scope} is the externally measured interval, then

$$e = t_{\text{ESP32}} - t_{\text{scope}} \quad (4)$$

High-level requirement 2 is satisfied when

$$|e| \leq 2 \text{ ms}$$

for at least 95% of verification trials. The response-conditioning circuit is required to introduce less than 1 ms of delay, while timer quantization contributes at most approximately 0.1 ms. This leaves approximately 0.9 ms of the ± 2 ms error budget for interrupt latency, signal variation, and other implementation effects. The final timing error will be verified experimentally using the two external test points rather than assumed from component specifications.

3. Ethics, Safety, and Standards

3.1 Ethical and Societal Considerations

Although this project presents relatively low physical risk, it raises several ethical considerations, including honest accuracy claims, privacy, human testing, and interpretation of results. Following the IEEE Code of Ethics [1], all timing claims will be based on measurements we perform rather than specifications taken directly from the ESP32 datasheet [4]. We will clearly distinguish measurement resolution from accuracy: resolution describes the smallest interval the timer can measure, while accuracy will be established by comparison with an oscilloscope or logic analyzer.

A reaction-time score only represents how quickly a user responded under the conditions of this test. It will not be presented as a measure of intelligence, athletic ability, driving ability, or health. The device is intended only for training and measurement and should not be used to make medical, employment, or fitness-for-driving decisions.

Bluetooth logging introduces a privacy concern because measurements may be associated with individual users. The device will transmit only the information required for its training function: a user-chosen identifier, reaction time, and trial type. Names, health information, and demographic data will not be collected.

Development testing will focus on validating device performance rather than drawing conclusions about human populations. If the project is later expanded into systematic human-subject research intended to produce generalizable knowledge, we will contact the University of Illinois Office for the Protection of Research Subjects and obtain the appropriate IRB determination or approval before collecting research data [2]. Other users will participate voluntarily and with their consent.

The device also has societal, economic, environmental, and global benefits. It provides a lower-cost way to train reaction time using dedicated hardware rather than a phone or computer. Reusable electronics and replaceable buttons and LEDs reduce disposable components. Because the device operates locally using lights, sound, and physical buttons, it does not require internet access, a specific phone platform, or a particular language.

3.2 Safety

Electrical risk is limited because all external supply rails are 5 V or less. During PCB bring-up, we will use a current-limited bench supply, verify each power rail before installing or powering sensitive components, and operate all components within their rated limits. The motor driver will include transient suppression to protect the control electronics from inductive voltage spikes.

The rotating encoder disk is the primary mechanical hazard. The disk, shaft, and coupling will be fully enclosed whenever the motor is operating to prevent contact with fingers, hair, or loose clothing. The

enclosure will require a tool to open, and the motor will be disabled before servicing. The enclosure will also prevent the user from seeing the encoder position and anticipating the stimulus.

The buzzer will be limited to approximately 85 dBA at 0.5 m, and stimulus tones will be brief. For comparison, OSHA specifies a permissible exposure level of 90 dBA for an 8-hour exposure [6], so normal operation will remain well below the corresponding exposure duration.

During assembly, we will follow University of Illinois Division of Research Safety soldering guidance [3]. Soldering will be performed with appropriate ventilation, energized boards will not be soldered, hot tools and components will be handled carefully, eye protection will be worn when appropriate, and hands will be washed after soldering. Lead-free solder will be used where practical. The project does not use high-voltage supplies or lithium batteries, reducing additional electrical and fire hazards.

3.3 Standards

The module carries FCC certification for its wireless transmitters [5], and we will preserve the approved antenna configuration and follow Espressif's PCB placement and antenna-clearance recommendations. The completed device will be designed with the requirements of FCC Part 15 in mind [7], recognizing that use of a certified radio module does not automatically remove all regulatory requirements for the finished device.

PCB conductor spacing, trace design, and related layout practices will follow IPC-2221C, *Generic Standard on Printed Board Design* [8]. The rotating encoder assembly will follow the risk-assessment and risk-reduction principles of ISO 12100:2010 [9], including guarding moving components that could present a mechanical hazard.

References

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- [8] IPC, IPC-2221C: Generic Standard on Printed Board Design. Bannockburn, IL: IPC, 2023.

- [9] ISO, ISO 12100:2010, Safety of Machinery—General Principles for Design—Risk Assessment and Risk Reduction. Geneva, Switzerland: ISO, 2010.