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Limora: A Synchronized Multimodal System for Real-Time Cognitive Load Monitoring in Educational Environments

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ABSTRACT

Cognitive load, the total mental effort required to perform a task, is crucial for assessing attention, stress, and learning performance. However, accurate measurement remains challenging as many existing monitors rely on single-sensor or unsynchronized devices, producing incomplete representations of cognitive activity. According to Cognitive Load Theory (Sweller), increased mental effort during complex tasks is reflected in physiological changes such as pupil dilation and autonomic activation, serving as reliable indicators of cognitive effort, yet their synchronized dynamics during academic tasks are rarely analyzed in controlled educational settings. This study introduces Limora, a synchronized dual-sensor system for cognitive load measurement that simultaneously records pupil diameter and skin conductance. Integrated architecture aligns both data streams through temporal synchronization, enabling cross-modal analysis of physiological responses. Pupillary fluctuations are captured using a webcam integrated with Pupil Capture software, while electrodermal activity is recorded via a Raspberry Pi connected to a Galvanic Skin Response sensor on the middle and index fingers. 40 high schoolers will complete a three-phase protocol using Limora, where stimuli are presented through PsychoPy, generating synchronized event timestamps. Tasks include a baseline fixation, an arithmetic task inducing working-memory load, and a Stroop interference task targeting cognitive stress. Data will be preprocessed by removing blinks, smoothing, and baseline-correcting pupil signals, while electrodermal activity will be separated into tonic skin conductance level (SCL) and phasic electrodermal response amplitudes (SCR). Mean and peak pupil dilation will indicate attentional effort, whereas SCL and SCR will reflect autonomic arousal. Normality will be assessed using the Shapiro–Wilk test. Repeated-measures ANOVA with Bonferroni-corrected post hoc tests will compare physiological responses across conditions, and Pearson correlation will examine associations between pupil dilation and electrodermal activity. The study aims to determine whether synchronized multimodal physiological signals provide deeper insight into cognitive load than single-sensor measurements, supporting potential applications in educational environments.

LOW-COST MULTIMODAL HARDWARE INTEGRATION

Cognitive load cannot always be fully understood through behavioral performance alone, as similar outcomes may reflect different levels of mental effort. To address this limitation LIMORA combines webcam-based pupillometry and Raspberry Pi–based electrodermal activity (GSR) sensing within a synchronized dual-sensor system. Recording both signals simultaneously allows attentional and physiological responses to be examined together throughout task performance. **LIMORA Framework:** A low-cost dual-sensor system combining webcam-based pupillometry (25 Hz) and Raspberry Pi-based electrodermal activity sensing (100 Hz). PsychoPy-generated event markers synchronize both physiological streams during task performance.

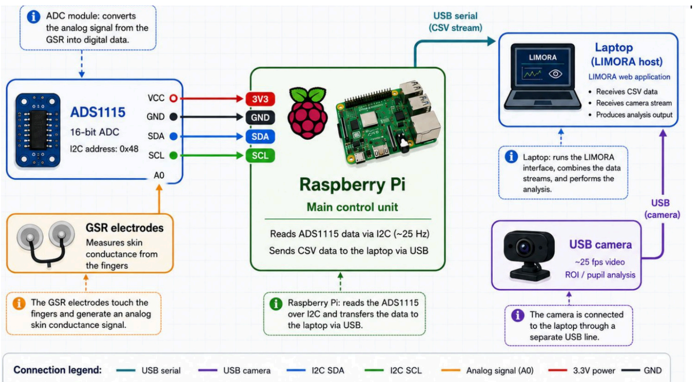


Figure 1. Limora hardware system diagram — GSR electrodes, ADS1115 ADC, and USB camera feed into the Raspberry Pi, which synchronizes and streams all data to the Limora laptop host for analysis.

Figure 3. Experimental setup — participant seated at desk with Limora laptop running the task software, eye tracker camera, and GSR wristband sensor.

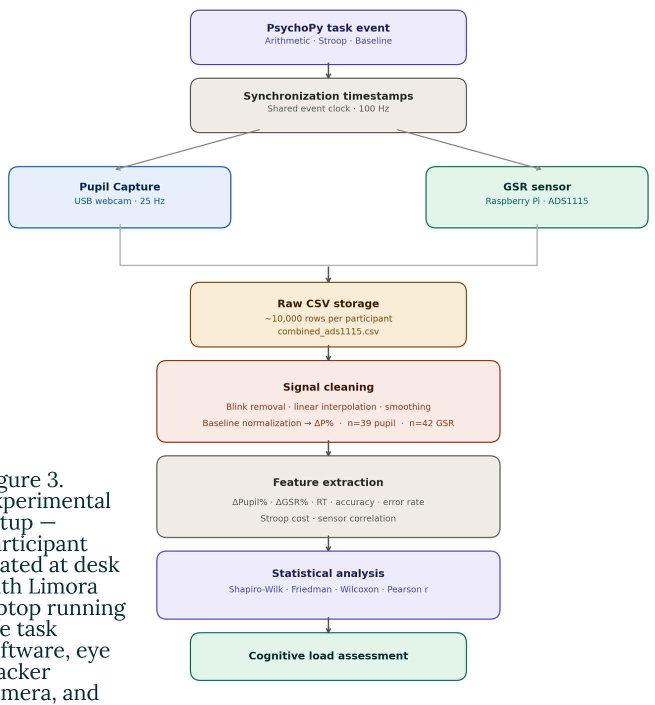


Figure 2. Limora data pipeline — dual-sensor acquisition, signal cleaning, and statistical analysis from stimulus to cognitive load output.

PARTICIPANT PROFILE

Participants were selected from a relatively narrow age range to reduce age-related variability in physiological responses. This helped create a more comparable dataset and allowed cognitive-load responses to be examined under similar developmental conditions.

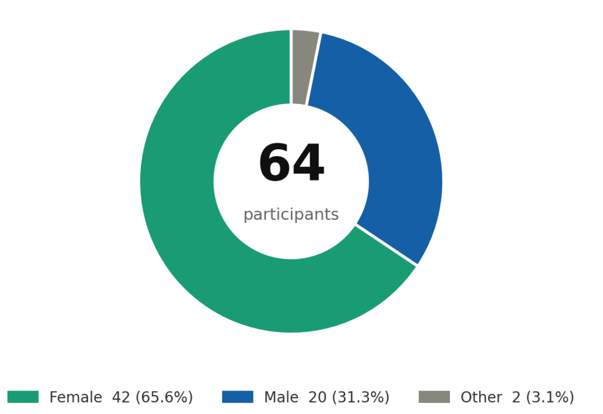


Figure 4. Gender distribution of enrolled participants (N = 64) — 65.6% Female, 31.3% Male.

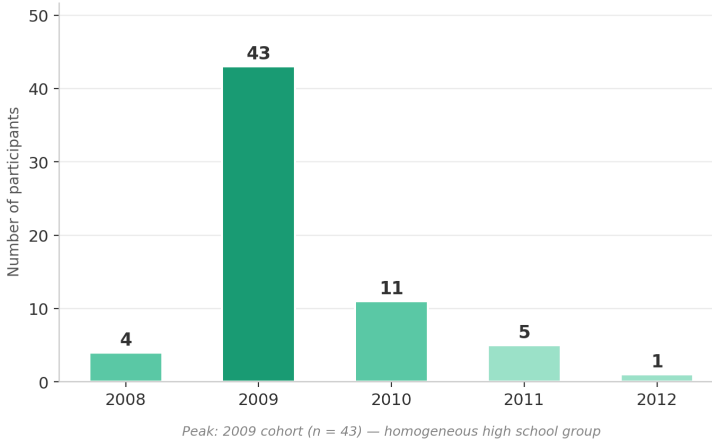


Figure 5. Birth year distribution — peak at 2009 (n = 43), confirming a homogeneous high school cohort.

SIGNAL PRE-PROCESSING & QUALITY ASSURANCE

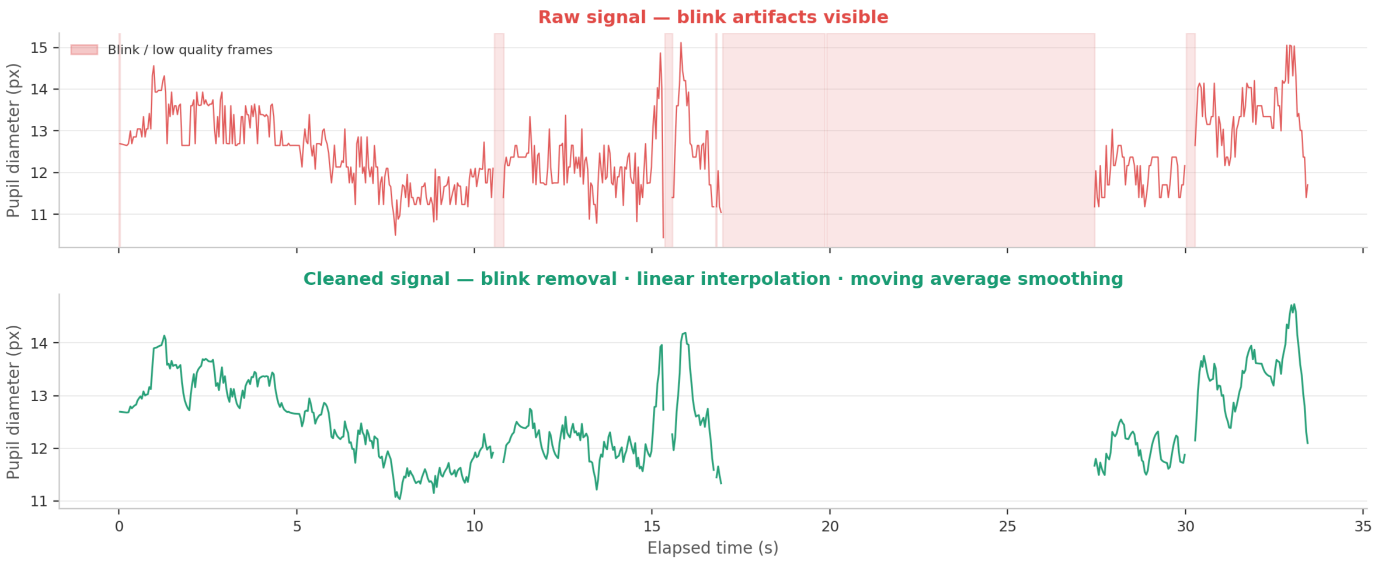


Figure 6. Signal Pre-Processing — raw pupil signal (red) contains blink-induced dropout artifacts; cleaned signal (green) is reconstructed via automated blink detection, linear interpolation, and moving average smoothing.

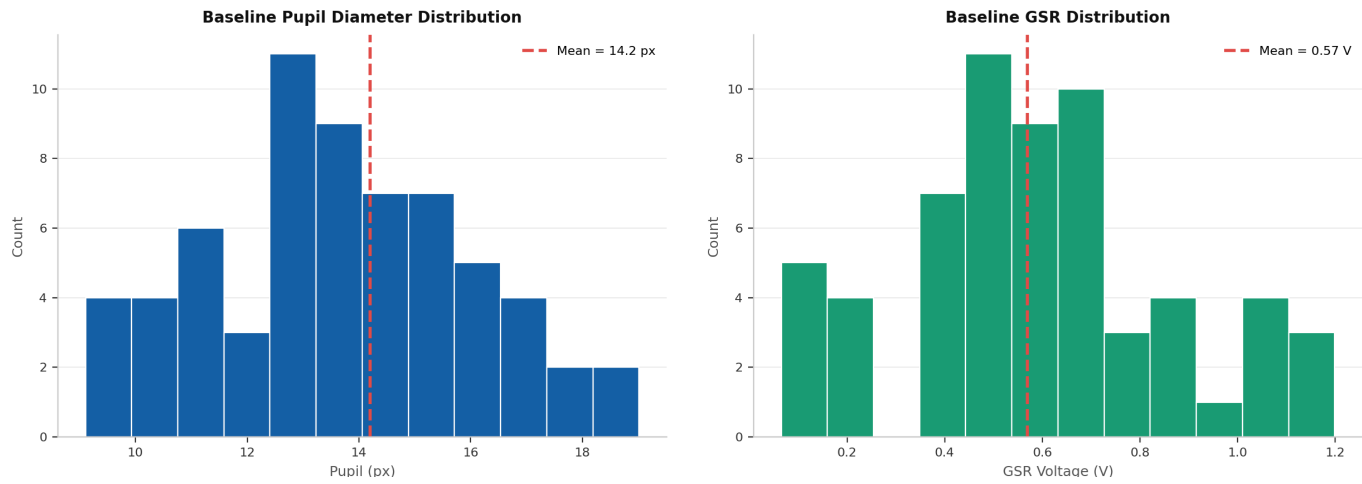


Figure 7. Baseline phase — resting pupil diameter (mean = 14.2 px) and GSR voltage (mean = 0.57 V) used as individual reference values for ΔP% normalization.

Physiological measurements are often influenced by blinking, head movement, and individual baseline differences. LIMORA therefore applies automated preprocessing and normalization procedures before analysis. These steps improve signal quality and help ensure that observed changes are more likely to reflect task-related cognitive processes rather than measurement noise.

BEHAVIORAL LOAD VERIFICATION

The arithmetic task was designed to increase working-memory demand across difficulty levels. Participants generally responded more slowly and made more errors in the harder condition, suggesting that greater mental effort was required to complete the task successfully.

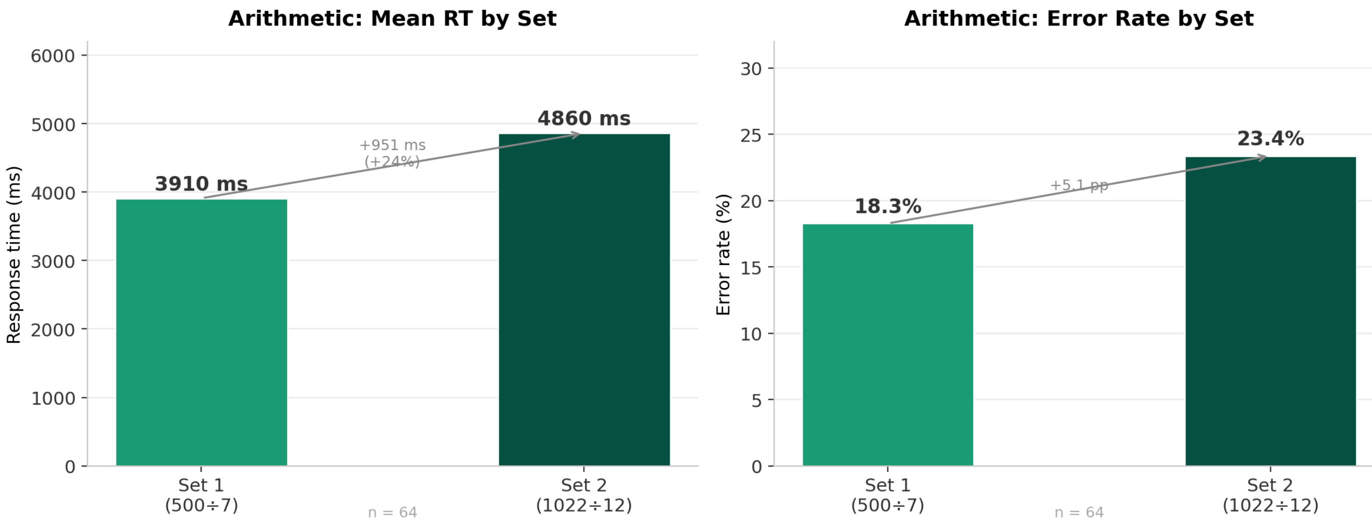


Figure 8a. Arithmetic mean RT increased from 3910 ms to 4860 ms (Δ = +951 ms, +24%) as working memory load increased from Set 1 to Set 2.

Figure 8b. Arithmetic error rate rose from 18.3% to 23.4% (+5.1 pp) confirming step-wise cognitive load increase.

SYNCHRONIZED MULTIMODAL PHYSIOLOGICAL RESPONSE

Behavioral changes were accompanied by measurable physiological responses. As task difficulty increased, pupil diameter and electrodermal activity also changed, indicating higher levels of attentional engagement and physiological arousal. Together, these findings suggest that the multimodal framework was sensitive to variations in cognitive load.

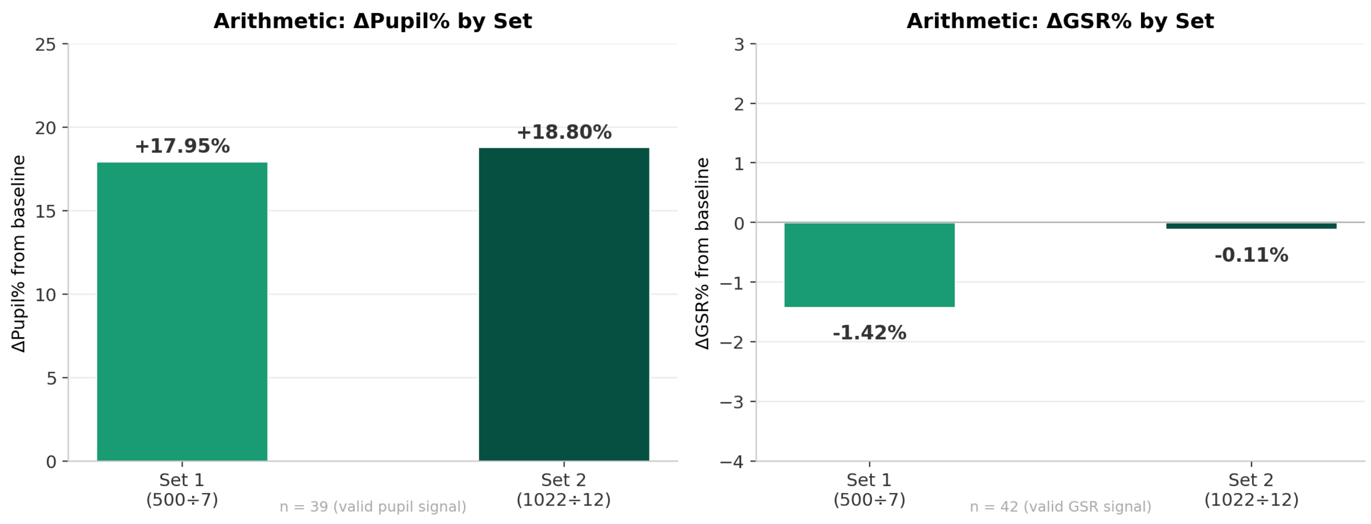


Figure 9a. Arithmetic ΔPupil% — pupil dilation expanded from +17.95% to +18.80% from Set 1 to Set 2, corroborating elevated attentional effort (n = 39).

Figure 9b. Arithmetic ΔGSR% — skin conductance suppression relaxed from −1.42% to −0.11%, indicating increasing sympathetic arousal with task difficulty (n = 42).

STROOP INTERFERENCE PERFORMANCE

The Stroop task was used to examine cognitive conflict and executive control. While participants became faster across conditions, accuracy declined as interference increased. This pattern suggests that participants prioritized responding quickly, leading to a decrease in accuracy as interference increased. Interestingly, the calculated Stroop cost was negative (−422 ms), indicating faster responses in the later interference conditions than in the initial condition. One possible explanation is a practice effect, as participants completed the task in a fixed sequence (T1→T2→T3) and may have become more familiar with the task over time. Therefore, the negative Stroop cost should be interpreted cautiously, as it may reflect learning effects in addition to changes in cognitive demand.

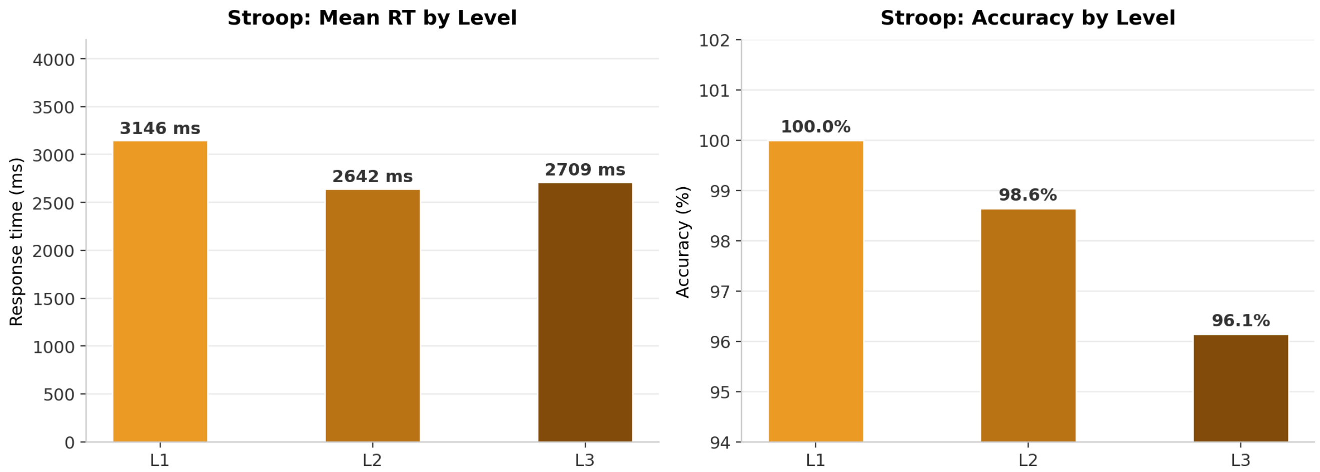


Figure 10a. Stroop mean RT — response time decreased from L1 (3146 ms) to L2 (2642 ms) then slightly recovered at L3 (2709 ms), yielding a negative Stroop cost of −422 ms (n = 64).

Figure 10b. Stroop accuracy — declined progressively from 100.0% (L1) to 98.6% (L2) to 96.1% (L3), confirming a speed-accuracy trade-off under increasing interference (n = 64).

CROSS-SENSOR CORRELATION

The pupil and GSR sensors showed different response patterns across tasks, suggesting that they may capture related but distinct aspects of cognitive processing. While pupillometry is commonly associated with attentional effort, electrodermal activity reflects changes in physiological arousal. Using both measures together therefore provides a broader view of cognitive load than either measure alone.

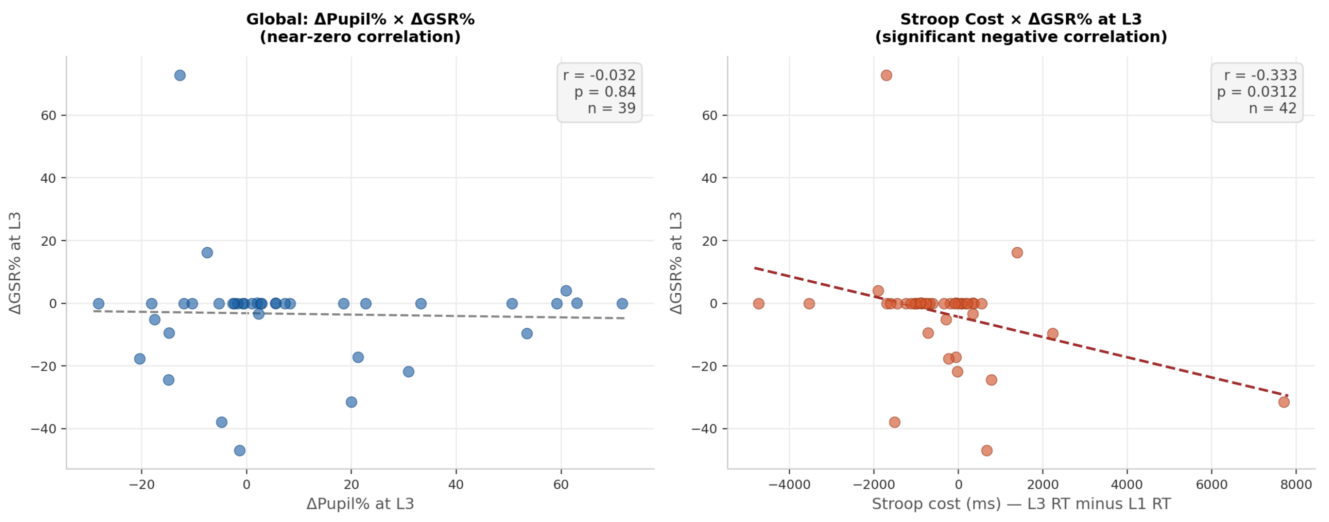


Figure 11a. Global sensor correlation — near-zero correlation between ΔPupil% and ΔGSR% at L3 (r = −0.032, p = 0.84, n = 39), confirming physiological dissociation between the two sensors.

Figure 11b. Stroop cost × ΔGSR% at L3 — significant negative correlation (r = −0.333, p = 0.031, n = 42); participants who accelerated most under maximum interference showed the highest autonomic stress.

STATISTICAL INDICATION

Statistical analyses indicated that several observed differences were unlikely to be explained by chance alone. Significant effects were detected despite the variability expected in a classroom-based study, suggesting that the LIMORA framework can identify meaningful changes in cognitive load under realistic educational conditions.

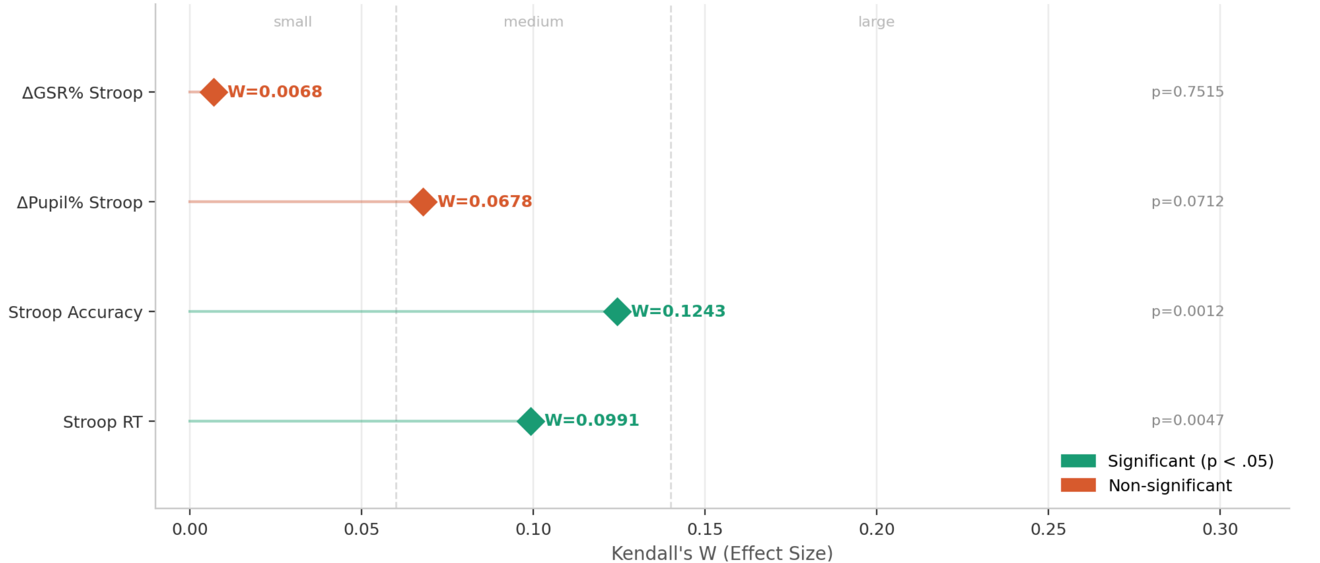
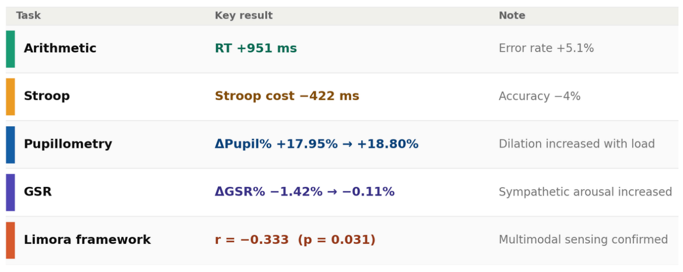


Figure 12. Effect size forest plot — The near-zero correlation observed between ΔPupil% and ΔGSR% at the highest difficulty level (r = −0.032, p = 0.84, n = 39) did not provide evidence of a significant relationship between the two physiological measures. Rather than confirming dissociation, this null result is consistent with the possibility that pupillary and electrodermal responses reflect partly independent physiological processes. However, this interpretation should be treated cautiously given the sample size and the limitations of drawing conclusions from non-significant findings alone.

DISCUSSION & CONCLUSION

LIMORA demonstrated the feasibility of synchronized multimodal sensing in an educational setting and suggested that behavioral performance alone provides only a partial view of cognitive load. By integrating pupillometry and electrodermal activity, the system captured both attentional effort and physiological arousal, providing additional insight beyond response time and accuracy alone. Although participants responded faster during later Stroop conditions, the observed negative Stroop cost likely reflects practice effects resulting from the fixed task sequence rather than reduced cognitive demand. These findings support the potential of low-cost multimodal sensing as a practical approach for cognitive-load assessment and future adaptive learning technologies.



Task	Key result	Note
Arithmetic	RT +951 ms	Error rate +5.1%
Stroop	Stroop cost −422 ms	Accuracy −4%
Pupillometry	ΔPupil% +17.95% → +18.80%	Dilation increased with load
GSR	ΔGSR% −1.42% → −0.11%	Sympathetic arousal increased
Limora framework	r = −0.333 (p = 0.031)	Multimodal sensing confirmed

Figure 13. Key results summary — behavioral and physiological outcomes across arithmetic and Stroop tasks, confirming synchronized multimodal cognitive load detection.

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