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Flipped Cognitive Classroom: developing a real-time cognitive load monitoring system for learning

Aula Cognitiva Invertida: desarrollo de un sistema de monitorización de la carga cognitiva en tiempo real para el aprendizaje

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Abstract- This paper presents a real-time monitoring system for measuring cognitive load in university students using various physiological sensors. The system integrates data from the Pupil Core eye-tracking device, Zephyr chest strap, Fitbit wristband, and Empatica E4 wristband to assess cognitive load through heart rate, respiratory rate, body temperature, electrodermal activity, and eye movements. The goal is to optimize teaching methods by analyzing cognitive load in real time, allowing instructors to adapt their materials to better engage students. A pilot test will be conducted in the Electronic Control Systems course, comparing the cognitive load generated using different teaching materials. The system's effectiveness is evaluated through students' physiological responses and performance on a test, highlighting the potential for personalized learning experiences. This development represents a significant advancement in cognitive load management and its application in educational settings.

Keywords: Flipped classroom, cognitive load, teaching materials.

Resumen- Este artículo presenta un sistema de monitorización en tiempo real para medir la carga cognitiva en estudiantes universitarios mediante sensores. El sistema integra datos del dispositivo de seguimiento ocular Pupil Core, la banda torácica Zephyr, la pulsera Fitbit y la pulsera Empatica E4 para evaluar la carga cognitiva a través de la frecuencia cardiaca, respiratoria, temperatura corporal, actividad electrodermal y movimientos oculares. El objetivo es optimizar los métodos de enseñanza analizando la carga cognitiva en tiempo real, lo que permite a los profesores adaptar sus materiales. Se realiza una prueba piloto en la asignatura Sistemas Electrónicos de Control, comparando la carga cognitiva generada con diferentes materiales. El sistema se evalúa a través de las respuestas fisiológicas de los estudiantes y su desempeño en una prueba, destacando el potencial para experiencias de aprendizaje personalizadas. Este desarrollo representa un avance significativo en la gestión de la carga cognitiva en entornos educativos.

Palabras clave: Aula invertida, carga cognitiva, materiales didácticos.

1. Introduction

The cognitive load theory emerged in the 1980s, providing predictions about how learning and problem-solving occur while considering mental resources and the effort invested in a given task (Sweller et al., 2019). This theory highlights that all information is first processed by the working memory, which has limited capacity and duration. Once information is stored in the long-term memory, these limitations in capacity and duration disappear. Cognitive load increases when unnecessary demands are imposed on the cognitive system; therefore, if cognitive load becomes too high, learning and task performance are impacted. This concept is particularly relevant in university lecture rooms, where students are exposed to different materials such as presentations, blackboard explanations, and videos, among others. Additionally, in these situations, different distracting stimuli may interfere with the learning task being carried out. Therefore, the more information teachers have about how cognitive load is evolving in students, the better they can manage and handle subject-related information to enhance student learning.

The theory of cognitive load distinguishes three types of cognitive load: intrinsic, extraneous, and germane (Paas et al., 2014). Intrinsic cognitive load arises from the interaction between the nature of the subject matter or task complexity and the learner's expertise. It is not directly related to the design of instructional material, which is why it is considered unmodifiable. Extraneous cognitive load occurs when instructional material contains more information than necessary, potentially becoming a distraction and hindering learning. This type of cognitive load increases the consumption of cognitive resources in working memory and does not facilitate the construction of schemas in long-term memory, thus failing to promote concept formation. Finally, germane cognitive load is associated with processes that contribute to the construction and automation of schemas. Cognitive load is additive, meaning that the total cognitive load imposed by a specific task is the sum of the three types described above. Therefore, studying the cognitive load generated by the instruction material used is essential.

Thus, our goal is to develop a comprehensive system that not only measures the cognitive load experienced by students but also utilizes this data to refine and adapt teaching methods. By doing so, we aim to promote an optimal cognitive load that enhances the learning process and improves student engagement and understanding.

2. CONTEXT & DESCRIPTION

Cognitive load can be measured by analyzing subjective variables, such as those collected by the NASA-TLX questionnaire (Hart et al., 1988), and objective variables, such as heart rate, respiratory rate, body temperature, electrodermal activity, and eye movements (Feidakis et al., 2019). However, subjective measures do not allow for real-time cognitive load assessment, whereas objective variables do (Naismith et al., 2015). As technology has advanced, objective variables related to cognitive load have been used (Ikehara et al., 2005). The proposed monitoring system consists of different sensors highlighting the Pupil Core eye-tracking and measurement device. This device allows for the measurement of aspects such as fixations, blinks, eye movements, and pupil size, which are related to cognitive load (Babu et al., 2019). However, for its use, the manufacturer provides two programs that do not allow real-time data acquisition. On the one hand, Pupil Capture enables the recording of a scenario, which can later be played back and exported in another program, Pupil Player to reproduce and export all relevant data. Since the goal of this work is to develop and implement a real-time monitoring system to gather cognitive load from university students, this section presents the development carried out to obtain, in real-time, all the relevant eye-tracking data necessary for measuring cognitive load*Sensors used*

The following vital signs are considered to properly assessed the cognitive load: respiratory rate, heart rate, body temperature and electrodermal activity.

- Zephyr Chest Band: The Zephyr device consists of an electronic module attached to a chest strap, which incorporates multiple sensors and a pressure sensor pad that detects the expansion of the ribcage. The device can measure size variations caused by the expansion and contraction of the thoracic cavity, allowing for the calculation of respiratory rate (Medtronic, 2025).

  The respiratory rate range is 0 to 120 breaths per minute with an accuracy of ±1. This device can transmit data in real-time and/or store it internally.

- Fitbit Wristband: The Fitbit Versa 2 wristband is capable of measuring and providing heart rate data (Fitbit, 2025). Heart rate is a highly sensitive indicator for assessing mental load and is typically measured using Photoplethysmography (PPG). These sensors consist of optical emitters that project light onto the skin, which is then refracted and detected by photodetectors. However, measuring heart rate with PPG presents several challenges, including sensor noise, light dispersion through different tissues, and variability due to different skin tones. To mitigate motion artifacts in PPG measurements, an accelerometer is used. Despite these challenges, PPG remains a widely used technique for calculating heart rate due to its ability to provide non-invasive and continuous measurements.

- Empatica E4 wristband: This wristband is designed to assess body temperature and Electrodermal Activity (EDA) (Empatica, 2025). The device provides physiological measurements through an EDA sensor and a temperature sensor. Body temperature data is measured in degrees Celsius using an infrared thermometer. This thermometer has a range of -40 to 115°C for skin temperature, with a resolution of 0.02°C and an accuracy of ±0.2°C. Meanwhile, the EDA sensor measures skin conductance with a resolution of 1 digit (approximately 900 picoSiemens) and a range of 0.01 microSiemens to 100 microSiemens. Both sensors transmit data at a sampling frequency of 4 Hz.

A. Pupil Core device

The Pupil Core device is an eye-tracking headset designed and manufactured by the German company Pupil Labs. The device consists of three main components:

- Two infrared spectrum eye cameras for detecting dark pupils, located on both sides of the face.
- A scene camera positioned at the front of the device, capturing the user's field of view with a maximum angle of 90º.

The infrared cameras have a maximum resolution of 800×600 pixels at 30 Hz, while the scene camera has a maximum resolution of 1920×1080 pixels at 30 Hz. The device uses the infrared camera to detect the presence of the eyeball and the subject's pupil.

B. Monitoring system

The integration of all devices facilitates the comprehensive collection of physiological data, allowing for a holistic assessment of the student's state and cognitive load. The developed system integrates multiple modules aimed at capturing, transmitting, storing, and processing all relevant information. The biosignals acquisition module consists of four devices, as shown in Figure 1, which collect student data and transmit it in real-time to a computer using two different protocols: MQTT [1]and ZMQ[2].

- The Pupil Core device is directly connected to the computer via USB.
- The Empatica E4 wristband, Fitbit, and Zephyr chest strap are connected via Bluetooth to a mobile phone, which acts as an intermediary to transmit the data to the computer.

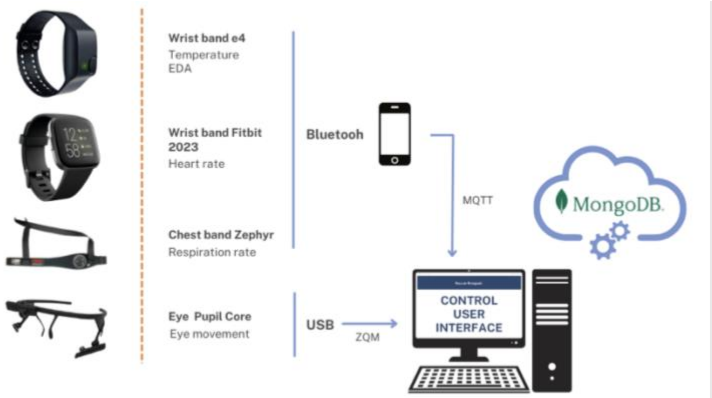


Figure 1. Monitoring system

[1] https://mqtt.org
[2] https://zeromq.org

3. RESULTS

A. System deployment

For the system's operation, a control interface has been implemented and developed, which allows for the collection of information from the different sensors as well as the storage of all data in a database.

- The control interface: it is a fundamental tool for managing and monitoring the data from the different devices. The interface, developed with Flask[3], is used for external supervision of the processes. It includes a control variable that allows enabling or disabling the collection of biosignals data, which is managed through a Start and Stop buttons. Additionally, the control variable sends the status of each biosensor to the database and ensures that data collection occurs only when instructed. Furthermore, it includes a graphical user interface that provides the real-time status of the sensors, displaying green when the data transmission is successful and red when it is not. The interface also requires the entry of a username, which serves as a unique identifier for everyone's biosignals, crucial for maintaining the integrity and organization of the collected data.
- Database: all the data collected from each of the sensors is stored in the MongoDB database. MongoDB is a NoSQL, document-oriented database that supports the storage and accessibility of large volumes of data with high flexibility for JSON-type data. This database provides a secure, highly scalable, robust, and efficient platform for handling large amounts of biometric data, facilitating subsequent analysis and interpretation of the data.

Additionally, to facilitate independent integration for data reception, the system has been containerized using Docker, which allows to run this system in all operating systems. The process of containerization involves packaging, deploying, and running applications within Docker containers. In this context, Docker is used to create, run, and deploy each application in an individual container. The process is as follows: a Docker image is generated for each data emitter, which contains the necessary code for data reception and storage, as well as all required libraries, tools, and dependencies. These images are then executed simultaneously in their respective Docker containers, with one image per container. Additionally, the control interface and the database also run in separate Docker containers within the computer. Therefore, the containerized system is composed of the following containers:

• rescuer-flask: provides the web interface.

• rescuer-mqtt: acts as the MQTT broker for communication. An MQTT broker is a component within the MQTT protocol that facilitates communication between de- vices. It functions as an intermediary that receives all messages published by devices (publishers) and distributes them to subscribed devices (subscribers) interested in those messages.

• rescuer-logger: collects the data sent to the mobile phone.

• pupil: receives the data sent by the Pupil Core.

• rescuer-mongo: the information handled by the phone and the Pupil Core data are sent to the MongoDB database for storage.

• game-mongo: used to store game data.

B. Teaching materials

Once the monitoring system has been developed, different teaching materials have been prepared to analyze the students cognitive load when dealing with them. The subject in which the system developed will be tested is the Electronic Control Systems. This subject is provided within the Electronics specialty in the second semester of the fourth year of the Telecommunications Engineering degree. Currently, the flipped classroom approach is used, providing students with theoretical materials pdf format that they need to study before the class. It has been thought that presenting the same concepts in video format will be more engaging for students, as it offers a more interactive experience. Therefore, the monitoring system developed will measure cognitive load and analyze the most effective teaching material to help students better integrate the concepts.

Two different control concepts will be presented to the students using two methods: a theoretical document in pdf format and a video. The pdf document is four pages long and includes text, formulas, and graphs, as shown in Figure 2. The video is eight minutes long, with the concepts being written down while they are explained. as shown in Figure 3. Some students will study the theoretical aspects using the pdf document, while others will do so by watching the video. Then, the same test will be accomplished by all the students to check their performance. During the time students go through the materials, all the relevant physiological data will be gathered.

The two control concepts for which the different materials have been prepared are:

- Proportional, derivative and integral actions.
- Two degrees of freedom systems.

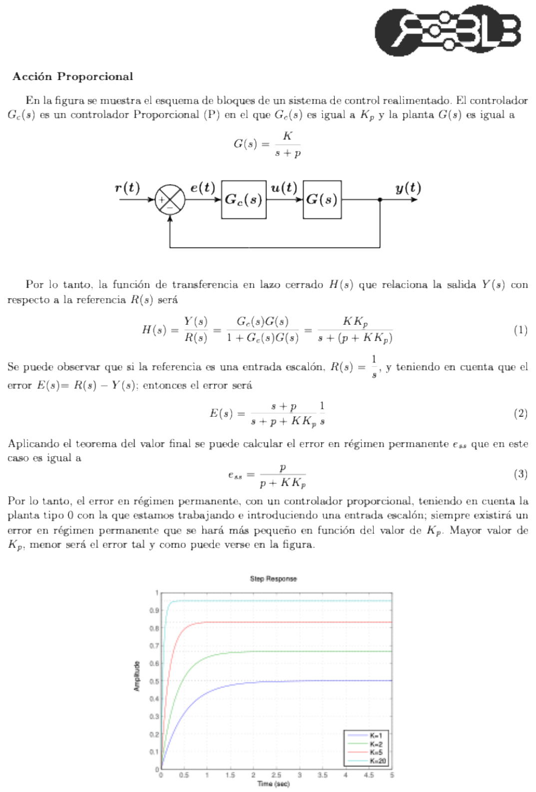
By using the monitoring system, the information gathered will allow to analyze and study if students invest more time in some parts of the materials than others. Additionally, this system will allow to measure how many times the material is studied before the student thinks that he or she has embraced the concepts.

Then, the same test will be used by all the students to evaluate their performance. The tests developed are:

- For the first concept, a remote laboratory will be used in which the different actions: proportional, integral and derivative can be used to explain how they contribute to the response of control systems. A small introduction is provided to the students with a manual explaining how to use the laboratory.
- For the second concept, a word document is provided with some questions regarding the two degree of freedom systems.

The time duration of each of the whole experiment, including studying the document and answering to the test will be no longer than 60 minutes

[3] https://flask.palletsprojects.com/en/stable/



Acción Proporcional

En la figura se muestra el esquema de bloques de un sistema de control realimentado. El controlador $G_c(s)$ es un controlador Proporcional (P) en el que $G_c(s)$ es igual a K_p y la planta $G(s)$ es igual a

$$G(s) = \frac{K}{s+p}$$

Por lo tanto, la función de transferencia en lazo cerrado $H(s)$ que relaciona la salida $Y(s)$ con respecto a la referencia $R(s)$ será

$$H(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G(s)}{1+G_c(s)G(s)} = \frac{KK_p}{s+(p+KK_p)} \quad (1)$$

Se puede observar que si la referencia es una entrada escalón, $R(s) = \frac{1}{s}$, y teniendo en cuenta que el error $E(s) = R(s) - Y(s)$; entonces el error será

$$E(s) = \frac{s+p}{s+p+KK_p}\frac{1}{s} \quad (2)$$

Aplicando el teorema del valor final se puede calcular el error en régimen permanente e_{ss} que en este caso es igual a

$$e_{ss} = \frac{p}{p+KK_p} \quad (3)$$

Por lo tanto, el error en régimen permanente, con un controlador proporcional, teniendo en cuenta la planta tipo 0 con la que estamos trabajando e introduciendo una entrada escalón; siempre existirá un error en régimen permanente que se hará más pequeño en función del valor de K_p. Mayor valor de K_p, menor será el error tal y como puede verse en la figura.

Figure 2. Pdf document created explaining the proportional action in control systems.

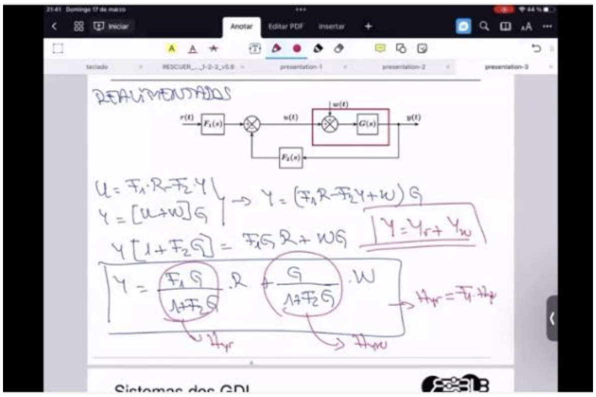


Figure 3. Video created in which the two degree of freedom systems are explained.

4. Conclusions

A system for real-time data acquisition has been successfully developed and integrated into a complex system consisting of four different devices. This makes this system one of the most comprehensive available for measuring cognitive load and integrating the most relevant vital signs in real time. This will allow for the analysis of the cognitive load of students when dealing with different learning materials to analyze how cognitive load evolves. Consequently, this monitoring system will allow to perform such analysis in future steps.

Furthermore, this system represents a crucial step towards effective cognitive load management, helping to mitigate the impact of cognitive overload on the teaching process.

Additionally, a pilot test of the monitoring system is planned with students, scheduled for April 2025, during the Electronic Control Systems classes.

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