

A Brain–Computer Interface Project Applied in Computer Engineering

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Abstract—Keeping up with novel methods and keeping abreast of new applications are crucial issues in engineering education. In brain research, one of the most significant research areas in recent decades, many developments have application in both modern engineering technology and education. New measurement methods in the observation of brain activity open a new frontier in engineering applications. Electroencephalogram (EEG)-based brain activity observation processes are very promising and have been used in several engineering studies, primarily for the implementation of control tasks. This paper presents the development, implementation, and assessment of an EEG-based engineering education project, in which engineering students applied the theory they had learned and improved their knowledge and skills in the area of observation and evaluation of electrical signals generated by brain activity and measured by biosensors. The main project goal was to develop and test a brain–computer interface that is able to measure the average attention level. The effectiveness of this project-based learning was evaluated by student questionnaire responses and analysis of students’ exam results; students who had participated in the project were shown to have higher levels of acquired knowledge.

Index Terms—Brain–computer interface (BCI), electroencephalogram (EEG), engineering education, project-based learning (PjBL).

I. INTRODUCTION

EDUCATION research has shown that learning that involves active student participation is more efficient in helping students acquire and then recollect new knowledge compared to learning associated with traditional lecture-based teaching [1], [2]. Furthermore, if this active participation is group-based rather than individual-based, students’ problem-solving, written, and oral skills improve, as well as their individual learning skills and cooperative abilities [2].

In the case of problem-based learning (PBL) [3]–[7], team-based learning [8], [9], and project-based learning (PjBL) [10]–[13], practical engineering skills can be effectively acquired. Being able to apply practical knowledge is a significant requirement in the field of engineering. This practical knowl-

edge can be acquired by carrying out practical activities, which can be in the form of a project [10]; this approach has also been applied in the multidisciplinary field of bioengineering [13]. In the project-based teaching method, the pedagogic strategy is a synthesis of cooperative, collaborative [14], [15], and autonomous learning, combined with teaching methods that promote student motivation in modern digital environments [16], [17].

This type of teaching is student-centric, with student activity being the key. This changes the role of the teacher; the traditional “teaching role” becomes that of a coordinator or a moderator. It has been noted that this increases efficiency in project-based engineering education [18]. During the project, in discussions led by the educator, students can share their ideas and experiences.

Various papers have discussed PjBL of measurement and control technology in education, in which practical skills are based on both software and hardware knowledge in the field of computer engineering. For engineering students to acquire practical skills, practical activities must be integrated into the learning process, as in the example of PjBL of electronic communication systems [19].

To increase their knowledge, students deal with real problems in a combination of theoretical lectures and practical laboratory tasks, which are supported by continuous feedback from the lecturer. The lecturer follows students’ progress and supervises their work, supporting teamwork and the development of problem-solving skills, in a collaborative environment [19].

Project-based practical learning activities help students to understand how systems operate and give practical insight into how they interact with the environment, as in the case of embedded systems [20]. References [21] and [22] demonstrate the traditional and modern teaching of control in control system laboratory sessions that help students to understand the modeling and control systems theories.

This paper describes a bioengineering project for computer engineering students in a multidisciplinary project-based engineering course. Students acquire practical knowledge of the structure and applications of brain–computer interfaces (BCIs) by creating a BCI based on the processing of brain signals. BCIs function as direct communication channels between the brain and other devices [23]; their design, development, and application are of great current interest, and they may have an important role in practical engineering education in the future.

Several universities have introduced new multidisciplinary courses in which students design and build biosensor-based systems. BCI development requires a multidisciplinary methodology since it requires knowledge of information technology,

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which is widely used in the field of computer engineering and bioengineering, cognitive science, neuroscience, and signal measurement, analysis, and processing.

The main goal of the project was for students to acquire multidisciplinary knowledge and skills in the field of signals and systems, and measurement and control theory by PjBL of BCI systems. This paper describes the pedagogical approaches taken and the project's topics, structure, schedule, development, implementation, and testing, as well as its evaluation.

The project motivates students to solve complex engineering problems and teaches them to cope with the challenges of planning and implementing real electroencephalography-based systems. The pedagogical approaches to this BCI project are based on those reported in the literature. Project teams had to prepare a report and demonstrate their work at the end of the course, as in the Mobile Robot Lab Project presented in [24]. The project's learning effectiveness and the learning improvements in the field of measurement and control theory were evaluated by a questionnaire and final scores, as shown in [19], [22], and [24].

Sections II and III describe the BCI-based project, its structure, pedagogical approaches, implementation, and main objectives. Section IV details the project activities and course elements, given as weekly tasks, along with project test results. Section V describes the project evaluation, and Section VI draws conclusions.

A. BCIs

Certain brain activity functions have been revealed in cognitive neuroscience research [25]. Understanding the brain's operation is of great importance in measuring and interpreting brain waves [26]. The electrical and magnetic phenomena of the neural function can be observed during brain operation by using a routinely applied approach, i.e., electrophysiology [27]. The most common method of electrophysiological observation is electroencephalography [28], whereby brain electrical signals generated by brain activity are measured and registered by biosensors [29]. Brain cells communicate by sending electric signals to each other; the more signals that are sent, the more electricity the brain will produce. An electroencephalogram (EEG) can measure the pattern of this electrical activity; these EEG signals are generally processed by a quantitative EEG (QEEG) method, in which the frequency spectrum of the EEG signals is observed [30].

Taking an EEG used to require complex, expensive, large, and immobile equipment, but technological developments have made mobile EEG biosensor-based embedded devices available for use in new applications, such as entertainment, control devices, or education. In these applications, it is a BCI that makes the connection between the brain activity observed by the EEG and the induced function [31]. Modern BCIs incorporate biosensors and modern signal processing units, are cheaper and more portable because of their simple structure, and have similar accuracy to clinical EEG devices [31], [32]. In engineering research, this technology is mainly used in control tasks, for example, controlling a robot [33], a helicopter [34], or a car [35].

II. OVERVIEW OF THE ENGINEERING PROJECT

The BCI-based project was an optional additional activity for undergraduate students enrolled in the required fourth-semester Signals and Systems (S&S) and the fifth-semester Measurement and Control Technology (M&C) courses in the seven-semester-long Computer Engineering program at the University of Dunaújváros, Hungary.

The main learning outcomes of these courses are that students are able to:

- 1) classify systems based on their properties and understand and exploit the implications of linearity, time invariance, and stability (S&S);
- 2) analyze, design, approximate, and manipulate signals to understand the sampling theorem and the Laplace and Z-transforms;
- 3) determine and use Fourier transforms and other signal analysis methods (S&S);
- 4) understand the application of control methods, proportional–integral–differential algorithms, and properties of control (M&C);
- 5) understand and analyze the design implications and interconnections of physical and control systems (M&C);
- 6) develop mathematical models for real physical and control systems and produce block diagram implementations of the mathematical models and control methods (S&S and M&C).

The project ran for two years, with 8 students in the first year and 12 students in the second year, with a lecturer and an assistant providing the basic knowledge required and helping in signal processing and evaluation.

In each year, the first semester of the project was organized in parallel with S&S, and the second with M&C. The first semester deals with BCI systems, and the second semester deals with the design and implementation relevant to S&S and M&C. Therefore, the survey of learning outcomes is based on the second semester M&C exam results.

The courses and project are based on previous experience from related courses in electrotechnics, electrical and digital technology, mathematics, C# programming, object-oriented programming, and various software development technologies.

The main challenges of the project are to motivate students toward EEG technology, EEG signal processing, and the application of BCIs. The BCI device in this project was effectively a computer-based attention level meter.

A. Project Topics

The courses necessarily began with an introduction to the concept of measurable EEG-based signals and the applications of EEG technology. The project's students start by learning EEG basics and then eventually learn to design EEG-based signal processing methods. First, they learn the discrete Fourier transform (DFT) to understand EEG signal processing in the frequency domain. Once they had acquired the basics of the signal processing method, the design and implementation of a computer-based attention level meter could begin.

The main objectives of the project are for students to improve their practical skills in computer engineering, learn practical measurement and control skills, and become familiar with the emerging scientific field of neuroscience. The project's learning outcomes are that students should become familiar with and improve their knowledge and skills in:

- the features of brain bioelectrical signals in brain activity and how to measure them, particularly by noninvasive EEG measuring methods;
- the main signal processing algorithms and their applications in observing mental or motor functions;
- the structure, operation, and planning of complex systems such as BCIs.

To achieve these learning outcomes, an EEG measuring unit is required that can easily interface with a computer and provide signals that are relatively easy to process. To this end, the NeuroSky MindWave headset, an inexpensive, mobile, and easy-to-fit EEG biosensor, was chosen for this project.

B. Project Schedule

In building the BCI, students had to collaborate to identify and solve the problems of each project planning stage. The teacher did not direct student activities, but instead coordinated and supported their work with tutorials and handouts containing relevant information, for example, descriptions of applicable signal processing algorithms and information to help students plan the software.

The project schedule is shown in Table I. The 2–3 h per week that students spend, on average, working on the project time did not have a negative impact on their other courses. The teacher's preparation time was similar to their teaching time.

C. NeuroSky EEG-Based MindWave Headset

NeuroSky has been developing EEG-based measuring devices for some years with the cooperation of universities such as Stanford University, Carnegie Mellon University, the University of Washington, the University of Wollongong, and Trinity College [39].

The MindWave EEG headset is a lightweight portable device with wireless communication [40]. The connection between attention and brain waves was observed in the 1970s, and an EEG-based attention analyzer was patented [41].

The method of attention measurement is based on the examination of the spectrum intensity determined by the DFT algorithm of brain waves. The spectrum can be calculated using samples of the brain signal.

The sequence of N complex numbers $x_0, x_1, \dots, x_{N-1}$ can be transformed into a sequence of complex numbers with periodic N [42], [43], i.e.,

$$X_k = \sum_{n=0}^{N-1} x_n \cdot e^{-i \cdot 2\pi k \frac{n}{N}} \quad k = 0, \dots, N-1 \quad (1)$$

where X_k encodes the amplitude and phase of a sinusoidal component of function x_n , which is a complex number. The brain wave intensity and the level of attention (the aim of this project) can be determined.

TABLE I
PROJECT SCHEDULE

Course Type	Topic	Weeks	Hours
Lecture	Introduction	1	2
Lecture	Basics of BCI systems	2	2
Lecture	Introduction to EEG and brain signals, cognitive psychology	3-4	6
Lecture	Biosensors, EEG headset	5-6	6
Lecture	Brain signals and attention	7	3
Laboratory	Special hardware training (UART communication, UART-USB conversion)	8-9	6
Laboratory	Special hardware training (signal condition, noise rejection, galvanic isolation, optocoupler)	10-11	6
Laboratory	Special software training (graphics programming, bar and line chart)	12-13	6
Laboratory	Design and building of BCI System	14-21	28
Laboratory	System testing, bug fixes, fine tuning	22-25	14
Laboratory	Human tests, evaluate results	26-28	10
Discussion	Discussion and presentation, project Assessments, discussion	29-30	4

III. PEDAGOGICAL APPROACHES AND PROJECT IMPLEMENTATION

A. Pedagogical Approaches

The concept of a problem-oriented project is to solve theoretical or practical problems. With this, engineering knowledge and skills are essential.

The design phase of the project emphasizes the concept of know-how; the implementation phase focuses on the use of practical knowledge. System design must consider alternatives: in this case, how many wet or dry sensors are used, and whether time or frequency analysis is applied. In one study, an EEG device with one dry sensor on the forehead and spectrum analysis were applied to measure attention [41].

Students begin by learning the basics of EEG signals, biosensors, signal processing, and the design, development, and operation of BCIs and then apply this knowledge in the implementation phase. The project was divided into two parts, the first giving a theoretical overview of BCI systems, with much interactive discussion of the main concepts involved, and the second tackling the project problem and tasks. The students

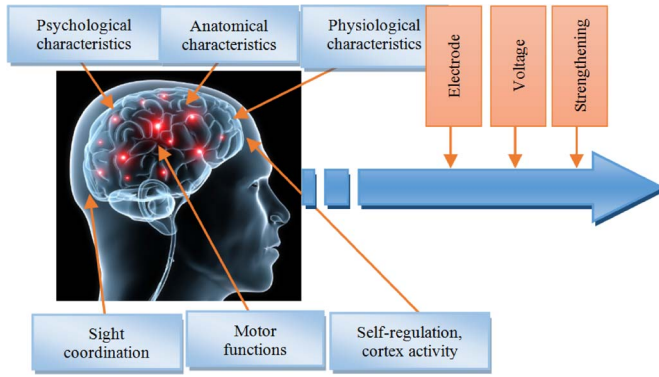


Fig. 1. Sample illustration: model of bioelectric signals.

were split into two teams of equal size to work on this second part. The first team designed and developed the project's signal processing and data storage aspects, and the second team worked on data evaluation, visualization, and realization of the attention level meter.

B. Project Implementation

The theoretical/descriptive training took the first to thirteenth weeks (13 lessons) of the semester, taught by a teacher and a technical assistant. The training tutorials were based on illustrations of the operation and main implementations of BCI systems, neurons, brain signals, and signal processing and visualization methods, as shown in Fig. 1. During this period, students became acquainted and elected to join either the first or second team based on their preferred area of interest.

Design, development, and implementation started in the 14th week. The two separate teams consulted with each other, with the help of the teacher, to coordinate their tasks within the wider project to define the information-sharing interface between the developed applications.

The teams continuously reported and presented their progress and results to the lecturer, who provided coordination and help. Within the teams, the students' teamwork improved as the project progressed. Both teams implemented their programs in Microsoft Visual Studio, a development environment that supports the object-oriented high-level C# programming language. Tables II and III summarize the project implementation steps and the main knowledge and skills gained by the two separate teams.

After the 23rd week, the two teams cooperated on the testing phase and on correcting system faults. Once they had finished the test phases, three further tests were carried out with students as test subjects. The data were evaluated, and the whole project implementation, activities, and results were presented and discussed at the end of the module.

IV. TESTS OF ATTENTION LEVEL METER AND STUDENT EXAMINATION RESULTS

Students tested the application using two methods. In the first method, activity levels were recorded for three subjects

TABLE II
PROJECT IMPLEMENTATION AND KNOWLEDGE
AND SKILLS GAINED FOR THE FIRST TEAM

Week	Tasks	Knowledge and Skills
14-16	Studying DFT algorithms, Fast Fourier Transform as optimized DFT algorithm	Application of Fourier series, sampling, noise, algorithmization of complex mathematical formula, optimization of computer calculations
17-20	Design of signal processing and data storage application	Static, dynamic, use-case views, database modeling, problem mapping
21-24	Implementation of signal processing and data storage application	Thinking in object-oriented model, algorithm imaging, database handling, SQL commands, logical thought
22-25	Test of signal processing and Data storage application	debugging, error detection, localization, development of test cases, unit and system, White and black box tests

TABLE III
PROJECT IMPLEMENTATION AND KNOWLEDGE
AND SKILLS GAINED FOR THE SECOND TEAM

Week	Tasks	Knowledge and Skills
14-15	Studying the theoretical operation of attention level meter	Application of Fourier series, optimization of computer calculations, EEG signal evaluation
16-20	Design of data evaluation and visualization application	Static, dynamic, use-case views, visualization modeling, problem mapping
21-24	Implementation of data evaluation and visualization application	Thinking in object-oriented model, implementation of graphical user interface, logical thought
22-25	Test of data evaluation and Visualization application	debugging, error detection, localization, development of test cases, unit and system, White and black box tests

(students) performing three activities, i.e., talking, watching a video tutorial on DFT calculation, and programming a quick-sort algorithm. In these three tests, their attention amplitude was recorded and tabulated in Excel, and the average value of attention and deviation was determined.

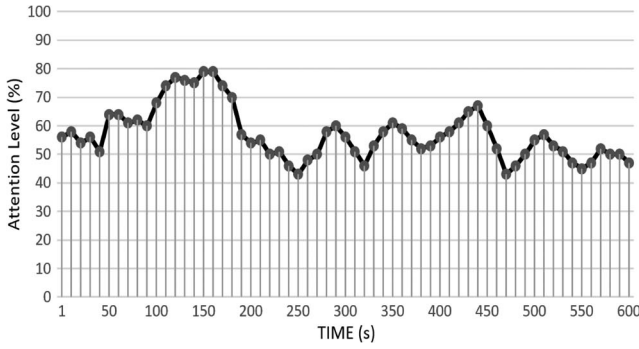


Fig. 2. Measured attention level of one test subject during programming.

TABLE IV
AVERAGE (AV.) AND STANDARD DEVIATION (S.D.) OF
THE MEASURED ATTENTION LEVEL (IN PERCENT)

Test subject	Conversation		Watch video tutorial		Programming	
	Av.	S.D.	Av.	S.D.	Av.	S.D.
A	43.2	8.1	49.9	8.5	57.2	9.3
B	45.1	7.8	46.3	8.1	55.5	8.7
C	39.8	7.2	43.7	7.4	53.3	8

The first of the three tests had the three subjects converse on various topics for 20 min, during which a 10-min measurement of their attention levels was taken. In the second test, the subjects each watched a video tutorial, during which their attention levels were recorded for 10 min. The third test had the subjects carry out a programming task, during which their attention levels were also recorded for 10 min. Fig. 2 shows the measured attention level of one test subject while programming.

The average and deviation of the amplitude of the recorded attention level values were determined for the three test subjects and are summarized in Table IV. The test results show that the programming tasks require more concentration than watching a tutorial video or having a conversation. In the second method, the effectiveness of the attention level meter was gauged by comparing the average attention value it recorded using a correlation calculation to a Conner's Continuous Performance Task (CPT) test employed in cognitive psychology [44]. The CPT test is implemented in the Psychology Experiment Building Language (PEBL) environment [45]. It examines concentration during a test that lasts for a relatively long time, approximately 14 min. In this widely applied test, the subject is shown 360 letters. In each case, unless the letter is an X, some kind of marking is required. Having finished the CPT test, the software immediately evaluates the results and provides them in report format. The test reports the number of correct evaluations of target stimuli, the major feature of attention level. Fig. 3 shows the variation of the test subject's attention level in the 1-s block of the CPT test, in which 18 stimulus items flashed on the screen

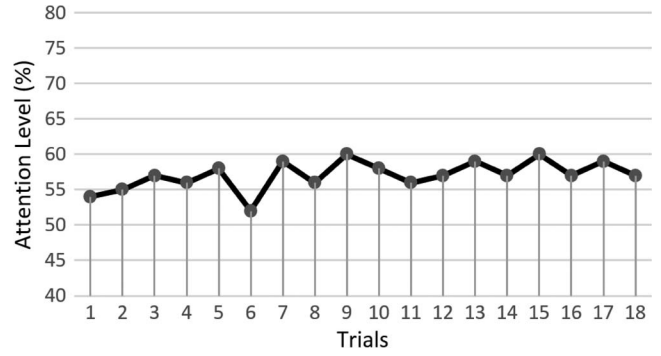


Fig. 3. Variation of the attention value of PEBL CPT (PCPT) in the 1-s block of time of the person under test.

TABLE V
RANDOM TEST RESULT OF PCPT

Test type	Average of correct answers	Correlation coefficient	p-value
CPT	315.1±6.2	0.61	<0.001
EEG	52.4±8.6		

for a period of 250 ms. The values of attention registered by the attention level meter started above 50% and rose slightly during the course of the test. In the second 2-s attention test, the attention level of the test subject was continuously higher than in the first attention test; values were never under 58% and achieved 80% in some cases.

In the last part of the test, the values of attention started below 50% and became more uneven. There was good agreement between the number of correct answers, the reaction time, and the standard deviation obtained during the CPT test. From the results of the CPT test, the number of successful trials related to the success of the test was statistically compared using the SPSS 20 package, with the value of the average attention given by the BCI system. To determine the relationship between the results of CPT and the attention level meter, the Spearman correlation coefficient was used, with the $p \leq 0.05$ value considered significant. The calculated correlation coefficient is shown in Table V.

The final demonstration was held in the last laboratory session of the semester, with a documentation report covering project design, implementation, and experimental results.

V. ASSESSMENT

The theoretical and practical knowledge and skills gained in the S&S and M&C courses were evaluated using the M&C exam results, and a student satisfaction questionnaire was completed at the end of the project. The exam was taken by 75 students, 55 of whom did not participate in the project (group 1-G1) and 20 who did (group 2-G2). The questionnaire was completed by the 20 G2 students who participated in the project. The exam results were used to evaluate the following hypothesis: that after completing the project, students had increased their theoretical and practical knowledge on signals

and systems and measurement and control theory. The exam results of students who did or did not participate in the project were statistically compared by *t*-tests to test the hypothesis.

A. Project Evaluation Survey

At the last course meeting, an eight-question survey was administered to students who participated in the project, to elicit their opinion of the project, using a five-point Likert-type scale of “A”: Strongly Agree; “B”: Agree; “C”: Unsure; “D”: Disagree; and “E”: Strongly Disagree.

Fig. 4 gives the mean of the results for each question, posed to two sets of G2 students, over two academic years. They were asked about their experiences in the engineering project and asked to evaluate the project in terms of their impressions and the practical knowledge acquired.

Based on the responses, students’ opinion of the project was very positive. They found it was interesting, helped them to understand and learn the basics of implementation in a complex system, improved their knowledge, and gave them experience of working in teams. The project topic was interesting to all the students, and 85% strongly recommended the project to others, despite the fact that only 25% thought that it was very easy to finish the project work.

B. M&C Exam Results

A three-part final exam addressing the material studied, difficulty levels, knowledge and problem-solving taxonomy [46], procedure, and interpretation was taken at the end of the M&C course by all students (G1 and G2). The first part was designed to evaluate knowledge, the second part for procedures, and the third part for interpretation. In the first part, the students had to answer closed questions on definitions, rules, and models, for example, classifying signals (see Fig. 5).

The second part consisted of open questions using steps the students were taught for solving well-known engineering calculations, for example, calculating the Fourier series of a given signal (see Fig. 5). The third part also used open questions and was designed to evaluate the understanding of the interpretation of engineering models and problem solving in real-world situations. Grades were ranked on a scale of 1–5, where 1 was unsatisfactory, 2 satisfactory, 3 neutral, 4 good, and 5 excellent. The overall student grade of the three-part test was the simple average of the results of the three parts. Students’ background knowledge was assessed based on the results of previously taken mathematics, electronics, and programming courses; *t*-tests show that the initial knowledge of G1 and G2 was similar (see Table VI).

C. Analysis of M&C Exam Results

All students (G1 and G2) took the final M&C exam; thus, the results could be compared for evaluation purposes. The final grade was calculated as a weighted average of scores on the three parts of the M&C exam. The grade average and standard deviation of the three separate parts of the exam and the result of *t*-tests are shown in Table VII.

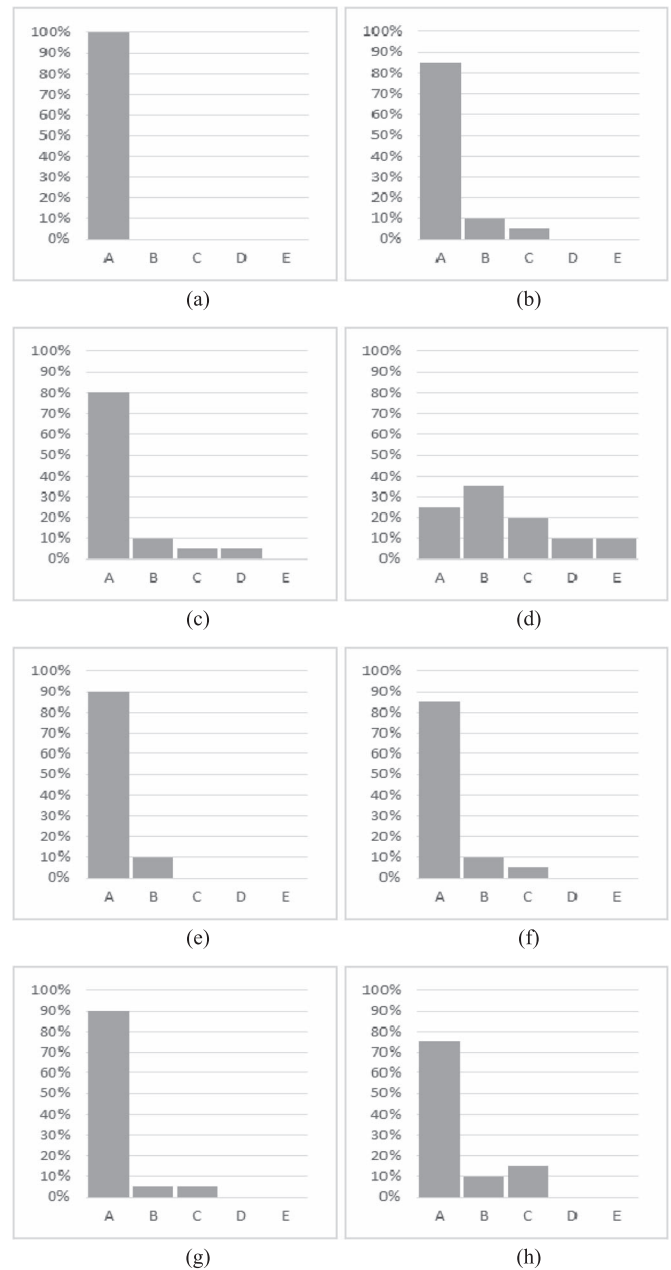


Fig. 4. Responses to the project questionnaire. (a) Q1: Did you find the project interesting? (b) Q2: Would you recommend the project to others? (c) Q3: Did the PBL technique help your learning process? (d) Q4: Was the project work easy to finish? (e) Q5: Did the project work help you understand and learn the basics of design and implementation of a complex system? (f) Q6: Do you think you can exploit the knowledge gained for future tasks? (g) Q7: Did the project work help you to extend your multidisciplinary knowledge? (h) Q8: Do you think the project helped to learn to work in teams?

According to the *t*-test performed on the results of students’ background knowledge survey, there is a small difference between G1 and G2, with a maximum *t* value of 0.53 and an effect size of 0.14.

In the M&C exam, the average grades for G1 and G2 were 3.636 (S.D. 0.91) and 4.2 (S.D. 0.768), respectively, showing a significant 0.564 average grade difference between the two groups ($p < 0.05$) in favor of G2, the group that participated in the project.

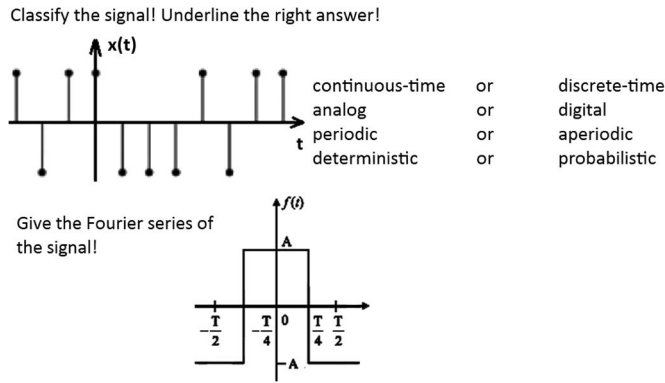


Fig. 5. Sample exam questions.

TABLE VI
BACKGROUND KNOWLEDGE (GRADE SCALE 1–5)

Exam studies	Group	Grade Av.	Grade S.D.	Effect size (d)	t
Mathematics	G1	3.036	0.769	0.14*	t = 0.53
	G2	3.15	0.933		(p < .05)
Electronics	G1	3.345	0.886	0.05*	t = 0.19
	G2	3.3	0.979		(p < .05)
Programming	G1	3.254	0.927	0.05*	t = 0.18
	G2	3.3	0.979		(p < .05)

* small practical difference ($d < 0.5$)

TABLE VII
EXAM RESULTS (GRADE SCALE 1–5)

Exam studies / Weights	Group	Grade Av.	Grade S.D.	Effect size (d)	t
knowledge 30%	G1	3.636	0.91	0.64*	t = 2.47
	G2	4.2	0.768		(p < .05)
procedure 40%	G1	3.436	0.855	0.6*	t = 2.32
	G2	3.95	0.825		(p < .05)
interpretation 30%	G1	3.254	0.865	0.63*	t = 2.43
	G2	3.8	0.833		(p < .05)

* medium practical significant difference ($d > 0.5$)

In the procedure tests, the average grade of G1 was 3.436 (S.D. 0.855) and that of G2 was 3.95 (S.D. 0.825). The difference in this case, i.e., 0.514, is also significant. Therefore, it can be stated that the students who worked on the project achieved better results than those who did not ($p < 0.05$).

In case of the problem-solving and primarily interpretation-based exam, similar differences could be seen. The average grade of G1 was 3.254 (S.D. 0.865), whereas that of G2 was 3.8 (S.D. 0.833), which shows a notable difference of 0.546 ($p < 0.05$).

According to the t -test results, the significance probability (p -value) was less than the significance level (0.05), indicating that there was a statistically significant difference in the results between those who participated in the project and those who did not, in all three parts of the exam, as shown in Table VII, with the former achieving significantly better exam results.

VI. CONCLUSION

This paper has presented an engineering project dealing with a new area of application of computer systems in psychological measurement. The implementation of the project included learning EEG-based measurement methods, EEG signal processing, and evaluating the relationship between brain waves and mental states, culminating in creating a new BCI system to realize an attention level meter. The project exposed students to many challenges and required them to exercise several types of practical skills and knowledge, such as high-level software programming language ability, implementation techniques for complex algorithms and results validation, and biomedical engineering understanding. The engineering project was very appropriate for computer engineering students, who are interested in the technologies applied, and it can motivate them to understand the design and implementation of a complex system. The combination of theoretical and laboratory activities increased students' knowledge and skills in the field of BCI systems, such as S&S and M&C. During the laboratory project work, participants acquired new knowledge of collaborative work, system design, implementing complex signal processing algorithms, and evaluating the results. The project's subject matter was drawn from many disciplines and can be applicable in several fields of computer engineering. Several discussions took place about the various challenges of the work and the solutions adopted to overcome these problems.

The main advantages of the work are that the project members encountered new system design and test patterns, software development technologies, the EEG-based measuring, and signal processing methods. Moreover, as a consequence of the project, the potential applications of BCI systems became known to participants. The project provides an excellent opportunity for the students to discuss and solve practical engineering problems, work in teams, and achieve a joint result by PjBL. Although the number of the participants was limited, the exam results show significantly better grades for students who participated in the project (G2), despite the initial knowledge levels of G1 and G2 being similar. Importantly, the project also gave students an interdisciplinary experience, marrying engineering knowledge with bioengineering science. The presented PjBL model provides a good framework to implement practical courses related to the multidisciplinary field of bioengineering and improve students' knowledge and skills in topics of S&S and M&C.

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