Juniper Publishers
key to the Researchers

THE IMPORTANCE OF DEMONSTRATIONS IN CHEMISTRY LESSONS, A COMPLETE STUDY SUPPORTED BY NEUROSCIENCE TECHNOLOGY

TRENDS IN TECHNICAL & SCIENTIFIC RESEARCH

The Importance of Demonstrations in Chemistry Lessons, A Complete Study Supported by Neuroscience Technology

Alejandro Cabrera Garcia[1]*, Olga Mykhaylyuk[2] and Vicent Gasso[1]

[1]European University of Valencia, Paseo de la Alameda, Spain

[2]Polytechnic University of Valencia, Camino de Vera, Spain

***Corresponding author**

Alejandro Cabrera Garcia, European University of Valencia, Paseo de la Alameda, Valencia, Spain

Published By :

Juniper publishers Inc.

United States

Date: July 09, 2021

Index

Abstract

Stoichiometry and the concepts of limiting reagent, excess reagent and reaction yields are a fundamental area of knowledge within the study of chemistry which accompanies students along their education path within this discipline. Unfortunately, this knowledge field is usually difficult to assimilate at first. In this sense, there is an open debate on whether these didactic contents could be learned through classroom demonstrations in order to improve the students' understanding and long-term memorization. However, up to now, there is still no consensus among the different authors on how positive or negative this methodology could be. This research uses neuroscience techniques, specifically electrodermal activity, electroencephalography and eye-tracking for evaluating attention response while classroom demonstrations in the instruction of stoichiometry are performed before first year high school students. Also, we have carried out an in-depth pilot study using academic tests, questionnaires, self-concept tests and interviews with students and teachers to evaluate the use of demonstrations in the classroom during the instruction of stoichiometry to the students. The results of this study support the efficiency of this methodology on the basis of attention as a constituent part of the increased cognition levels deriving from an effective response in the students and aim to promote the use of these tools for the development and validation of new teaching methodologies.

Keywords: Stoichiometry; Neuroscience; Electroencephalography; Eye tracking techniques

Introduction

Stoichiometry in chemistry learning

Stoichiometry is a chemistry learning unit studied in secondary and high school education paths in most parts of the world. It is later studied in most university degrees of the science and engineering areas. Chemical reactivity and stoichiometry, specially, are a fundamental part of organic and inorganic chemistry, analytical chemistry, physical chemistry, chemical engineering and biochemistry and their associated professional fields. It is therefore essential that pre-university students appropriately develop their stoichiometry competences to facilitate their subsequent extension and further study throughout their future studies and careers.

Unfortunately, the experience of secondary education students with these concepts is associated with strong misconceptions and lack of motivation [1]. There is abundant research on the problems associated with learning and teaching stoichiometry and related concepts [2-4]. Stoichiometry is considered by students as one of the most difficult subjects in introductory chemistry courses [1]. According to the literature, the most difficult aspects to assimilate are the interpretation of stoichiometric coefficients and subscripts, the establishment of the limiting reagent and the concept of molar proportions in relation to molar masses [1,5-9].

Specifically, students often assume that substances react in equal molar numbers, molar proportions are normally confused with mass proportions and molar mass with total mass [5]. They tend to assume that the ratio of moles to units of atomic mass (uma) is always a one-to-one [9]. Students do not usually realize that subscripts indicate the number of atoms within a molecule, while stoichiometric coefficients establish the number of chemical entities in a balanced equation [8]. Students also tend to think that the number of moles of a given substance is preserved in any reaction [9] the proportion of reagent and product in a reaction is always one-to-one, ignoring the balance of chemical equations [1] and the limiting reagent is the one with the lowest stoichiometric coefficient [6,7] among others.

Scientific demonstrations: Trying to improve the students' chemistry perception and learning outcomes, many authors have proposed the use of scientific classroom demonstrations. A scientific classroom demonstration can be defined as a punctual illustration during a science lesson through something other than a conventional eye-catching aid device. It means not just a video tape or some presentation slides, which are directed by an instructor, with students observing the results. In some cases, the demonstration can follow the students' predictions about the results (active participation) to present and address the most problematic points in the lesson [10]. Some authors suggest that scientific classroom demonstrations can be as effective as laboratory approaches to stimulate student research, concept formation and information retention [11]. It has also been defended that these demonstrations increase the level of attention and participation of students in science lessons [12]. However, while some authors state that the application of scientific classroom demonstrations should be virtually universal in science lessons [13,14] other authors raise several reasons why some educators might choose not to include demonstrations in their instruction [15]. Specifically, Meyer, *et al*. [16] criticize that research in quantitative education is not very deep, which shows a great lack of knowledge of their potential when they are well executed. Tai, Sadler & Loehr [17] found no correlation between the frequency of chemical demonstrations in high school chemistry classes of university students and their grades in introductory chemistry courses, while Tai & Sadler [18] observed a negative correlation. Crouch *et al*. [19] state that students must actively participate to obtain gains in conceptual understanding. Other research [20] indicated that the increase in student engagement, performance measures and motivation (attitudes) were inconclusive about classroom demonstrations.

Pierce & Pierce [21] proved significant learning outcomes occurred in the evaluation of topics that were included in the classroom demonstrations but were not included in laboratory sessions. Interestingly, the mid-term and final exam scores indicated that the students who completed the post-demonstration written assessments did not get better results than the control group and in two of the three post-treatment exams performed significantly worse. One of the main promoters of classroom demonstrations in chemistry is Shakhashiri [22] in his book 'Chemical Demonstrations: A Handbook for Teachers of Chemistry', who argues how carefully planned demonstrations can have a positive impact on students' learning. However, others criticize the use of demonstrations noting that they require a lot of time and are often simply present for entertainment rather than educational reasons [23]. Currently, there is no convincing evidence for or against the educational benefits of these, perhaps the lack of a strong indicator reflects the difficulty of assessing the educational value of demonstrations [24]. In an attempt to assess the benefits of classroom demonstrations, Walton [24] conducted an empirical survey on a group of undergraduate students. To do this, students were asked to complete a questionnaire after having attended a lesson course that was complemented with chemical demonstrations. The results strongly support the idea that demonstrations are favorable teaching tools. Importantly, the results show that a large proportion of the students agreed that chemical demonstrations helped them understand theories. Here, there is a lively debate about the validity of using demonstrations in the classroom. Some authors defend them, arguing its effectiveness [24]. Others, on the other hand, reject them since they consider that they are only an entertainment or, what is worse, that they can lead to misunderstandings [18,21]. However, the arguments for these claims are often lacking in quantity [18,23].

On the other hand, the affective component of this type of sessions is rarely considered [25-27] either using questionnaires or emerging techniques commonly used in neurosciences which allow us to deeply understand how the mind of a student "accepts" the fact of facing a lesson whose academic contents are supported with simple and striking experiments that demonstrate the viewer what the instructor is talking about. Neuroscience opens up a wide range of study possibilities for the improvement of teaching methodologies [28].

Neuroeducation

Neuroscience has provided powerful tools such as functional magnetic resonance imaging or electroencephalography, which allow for analyzing the brain processes involved when performing cognitive tasks like the ones experienced during knowledge and skills acquisition [28]. Neuroeducation is an emerging scientific field that aims to explore the interactions between neurological processes and education in order to, for example, improve learning processes. The students' affection consists of constructs such as attitude, interest, motivation, self-concept, values and moral values. These six constructs play an important role in science learning [27]. Although many studies have indicated that addressing cognitive dimensions could promote students' chemistry learning achievements and improve the full effectiveness of chemistry learning, affective dimensions must be integrated into the consideration of student learning and teachers' teaching. Difficulties in measuring affective and cognitive dimensions have been resolved using neuroscience technologies. Nowadays, tools such as those described below are used to carry out this type of study [28].

Psychophysiological measurement techniques

Electroencephalography: Electroencephalography (EEG) is a non-invasive technique widely used in the study of brain activity obtained from a user's scalp [29] which is due to neuronal communication through electrical and chemical signals [29]. The electrodes of an EEG device capture the electrical activity, which is transformed through a Fast Fourier Transform (FFT) algorithm in order to identify distinct waves. Brain waves are classified by frequency into five types: Beta (14 - 30Hz) in active concentration activities, Alpha (7 - 13Hz) in relaxed activities, Theta (4 - 7Hz) during hyperventilation or drowsiness, Delta (up to 4Hz) During sleeping and Gamma (30 Hz or higher), during high mental activity. It has been found that brain functions are associated with different brain frequencies. However, there is no linear correspondence between a frequency band and a given brain function [29]. To the best of our knowledge, EEG technique has been used in chemical education research [30], but that it has not been applied to classroom demonstrations.

Measurement of electrodermal activity: Electrodermal activity (EDA) is the term used to describe changes in the electrical conductance of the skin. EDA includes two main components: the tonic component that comprises the level of electrical conductivity of the skin and the phasic component, called galvanic skin response (GSR) that result from sympathetic neuronal activity. EDA is a psychophysiological index sensitive to changes in autonomic sympathetic neuronal activity, which is correlated with emotional and cognitive states [31,32]. Autonomic responses in the skin such as sweating, piloerection and vasomotor changes can be caused by various emotional states through Papez's circuit in the limbic system [33]. In addition, the stimuli and tasks that attract and demand attention also cause an increase in EDA responses [33]. Therefore, the response of EDA could be used as an indicator of the student's engagement in the learning process. To the best of our knowledge, EDA has not been used in chemistry learning using classroom demonstrations.

Eye-tracking recording: Eye tracking techniques have the potential to reveal the attentional processes that contribute to learning. For example, the location, duration, and number of gazes on predefined areas of interest along with transitions between areas indicate the degree of attention allocated to these areas. These measures, combined with achievement tests, thinking aloud, or interviews, can shed light on how or why students do or do not acquire knowledge [34]. Studies on chemistry learning based on visual registration, eye movement, blinks, etc., have already been attempted but did not rely on live demonstrations due to the difficulty of following a dynamic process. Further detail is given below on how this dynamic process has been achieved.

Aim of the study: There is a lack of studies using psychophysiological measurements to understand and improve the use of classroom demonstrations in chemistry learning. Therefore, the aim of this study was to perform a complete study about classroom demonstrations and to address chemistry classroom demonstrations to the best way as a pilot study for future expansion and further exploring. This study was carried out by using neurosciences biometric measurement tools, specifically, electroencephalography (EEG), electrodermal activity (EDA) and eye-tracking recorders (ET) to better understand the students' cognitive processes during classroom demonstrations. Moreover, these measurements were complemented with semi-structured interviews with the subjects of the study. So, the research question is: Are classroom demonstrations truly effective in teaching the concepts of chemical reactivity in the first year at high school, both academically and emotionally?

Methodology

General features

The study was conducted on a chemistry session of a first-year high school class of 16 healthy students (9 women and 7 men, between 16 and 17 years old) at a private bilingual (Spanish- English) school in Valencia (Spain). The learning objectives of the session were to perform rigorous chemical reactivity and stoichiometric calculations, which were taught using the classroom demonstrations methodology. Different psychophysiological measurements and a semi-structured interview was performed on two students (a 16-year-old woman and a 17-year-old man), who previously provided, on a voluntary basis, a written informed consent from their parents or legal guardians to participate in the study. The psychophysiological measurement equipment used during the session consisted of two electroencephalography (EEG) systems, two electrodermal activity (EDA) systems and two eye-tracking recorder (ET) systems. The learning objectives analyzed in the research correspond to one of the didactic objectives of this particular course, specifically chemical reactivity and stoichiometric calculations. Five months prior to the investigation, these students had already been instructed in the concepts analyzed in this research by their corresponding teachers by means of a methodology familiar to them from their mainstream school courses, which included the viewing of videos and solving numerical problems.

Electroencephalic analysis

The EEG electrodes system used consisted of the EMOTIV EPOC+ by EMOTIV and the analysis of these results were performed by the the Emotiv Xavier Control Panel and Emotiv Xavier Test Bench softwares. The headband with the electrodes previously moistened with saline serum was placed on the students' scalp controlling the position of each electrode according to the positions recommended by the commercial supplier. Subsequently, it was calibrated using the EMOTIV Xavier software.

The EMOTIV EPOC+ consists of 14 independent electrodes, which are located as shown in Figure 1. The Emotive Xavier software incorporates an algorithm that evaluates brain wave signals by eliminating noise, thus facilitating the interpretation of equipment readings. It provides readings on six basic emotional parameters: Stress, Engagement, Interest, Excitement, Focus and Relaxation (Table 1). These parameters are measured in percentages with respect to the normal values of the brain under study. Each measurement is automatically scaled to adapt to its normal range and base level of each condition: the system learns its usual status and capabilities and provides an adjusted value that shows its relative performance on each occasion, compared to its general behavior in the range of 0 to 100%.

Table 1: Emotional parameters measured in the electroencephalic analysis.

Emotion	Description
Stress	Level of comfort with a current challenge [48].
Engagement	Level of brain immersion in an activity (opposed to boredom). It is a mixture of attention and concentration [59].
Interest	Degree of attraction or aversion to a stimulus, environment or activity, also known as valence [51].
Excitement	Physiological feeling with a positive value [57].
Focus	Depth of attention and frequency in which attention changes in time [49].
Relaxation	Ability to disconnect and recover from intense concentration [50].

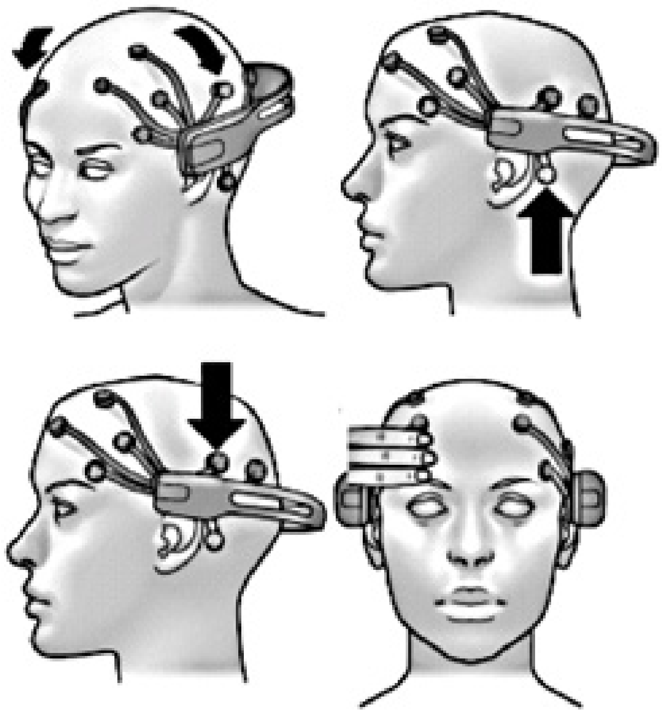


Figure 1: Location of EEG EMOTIV EPOC+ electrodes on the scalp. Image taken from the EMOTIV EPOC+ user manual.

Electrodermal activity analysis

The electrodermal activity (EDA) of the skin of the two selected students was also monitored using the eSense Skin Response electrodes by Mindfield Biosystems. This system measures the skin electrical conductance changes caused by micro-sweating. Changes in skin conductance at the surface, provide a sensitive and convenient measure of stress, emotion, cognition, and attention [31,33]. The sensors are placed on the fingers of the non-dominant hand of the selected students. Specifically, the electrode of the positive terminal is placed on the central or proximal part of the phalanx of the index finger. In addition, the electrode belonging to the negative terminal is placed on the middle or proximal phalanx of the middle finger. Conductance measures were taken continuously during the development of the lesson including chemical demonstrations. Matlab R2019a has been used to process the original data and analyze the results. The data of the unprocessed electrodermal activity signals were filtered with a low-pass filter (3 Hz cut-off frequency) to reduce motion artefacts and electrical noise.

Eye-tracking analysis

Mobile eye tracking recording was also implemented during the class with demonstrations. Eye gaze during the lesson was captured using a head-mounted eye tracker. The eye tracker had two infrared eye cameras that recorded binocular pupil and corneal reflections from the images of both eyes at a resolution of 640 × 480 pixels, at a framerate of 60 frames per second and a sampling rate of 60Hz. The eye tracker also had a world camera that captured a first-person, 90° diagonal field of view of the individual's environment at a resolution of 1280 × 720 pixels, a framerate of 60 frames per second and a 30Hz sampling rate. The eye tracking system's average gaze estimate accuracy was 0.6° of visual angle (0.08° precision). This system allowed for eye fixation information to be integrated with visual information from the perspective of the participant. The data were recorded with Pupil Capture v.0.9.12 on a laptop manipulated by one of the authors during the session. Prior to beginning any of the mobile eye-tracking tasks, the eye tracker was placed on the students' head, and eye cameras were adjusted to ensure that each of the student's pupils was captured by one of the two eye cameras. The experimenter then performed a 5-point calibration followed by a validation procedure. This procedure facilitated offline processing of the lesson attendance task so that the fixation could be corrected, provided that the student had good initial calibration. In this study, three Areas of Interest have been defined:

a) the demonstration objects

b) the instructional support slides

c) the teacher

A Complete Study Supported by Neuroscience Technology for the Analysis of Demonstrations in Chemistry lessons, A Case Study

In this study the following eye-tracking indicators were analyzed: FIXATION, which is defined when the participant's eyes remain looking at one specific place, considering it as the defined Areas of Interest, for 200 ms or more. The fixation is considered as an indicator of the perceived points of interest, and the duration of the fixation indicates the cognitive complexity of the information that is being acquired [35]. Total Fixation Duration (TFD), which is the time of the entire duration of the fixation for each area of interest and lesson stage, where each demonstration lasted a certain time, since they were present at each stage. Teacher and slides Areas of Interest were considered to last the same as the instruction. The Stage Duration of each demonstration is considered the time of each demonstration itself and its explanation that progress at the same time. The Percentage of Fixation is defined as the portion of fixation time with respect to the total lasting of the stage. Due to the different duration of each stage, the very useful parameter of Fixation Per Second was defined: this is the ratio between the number of fixations within a given area of interest in a concrete stage and the duration of this stage in seconds. Finally, Reviews, which are considered as the number of times that the student's point of view returns to an Area of Interest from which he has previously left. These indicators defined in the data analysis are useful for interpreting the results.

Semi-structured interviews analysis

After the chemical demonstrations session, a semi-structured interview was carried out in relation to the selected subjects' perceptions and opinions about the teaching methodology experienced during the session. This interview was video recorded and conducted in Spanish, which was the mother tongue of the interviewees. Moreover, the students were connected to the EDA system in order to extract the physiological responses during the interview. The recorded interviews were transcribed verbatim and a qualitative analysis was carried out with the help of Atlas.ti 7.5 software. A codification was used mainly focused on the opinion about the effectiveness, validity, valence and the feasibility of the use of classroom demonstrations in chemistry classes.

Pre-test

During the investigation, students were given a pre-test, one week before the class with chemical demonstrations. This questionnaire contained 9 multiple-choice questions, with 4 options to choose from. 6 of these questions were related to concepts and questions of stoichiometry, limiting reagent and excess reagent and the other 4 to reaction yields and a numerical problem with 4 sections, the first two referring to stoichiometry, limiting reagent and excess reagent, and the other two to reaction yields. The questions asked in the pre-test are included below, together with a table with the distribution of answers by the students and the correct answer in each case of the multi-choice options (Table 3). The 9 multi-choice options were assigned 1 mark to each of them and each section of the problem scored 0.25 points, amounting to a total of 1 mark, which completes the maximum score of 10 marks for the pre-test. Each question was analysed separately, thus outlining the misunderstandings of the students, in the same way as the problem that, in addition to the resolution strategies, reveals the errors committed in it.

Pre-test of chemical reactivity concepts

1. Given the general chemical equation: $A + B \rightarrow C + D$, where we must calculate the amount of product C formed in the reaction. What is the first step we must take?

a) Determination of the limiting reagent

b) Stoichiometric balance of reaction coefficients

c) Transform the quantities of the initial reagents into the same units

d) All of the above are correct

2. Excess reagent is defined in a chemical reaction as:

a) That reagent that is in smaller proportion based on the balanced chemical equation

b) That reagent that does not intervene in the chemical reaction

c) That reagent that is not completely consumed in a chemical reaction

d) That reagent that is completely transformed into a reaction product

3. When we mix sodium bicarbonate and vinegar, the following chemical reaction occurs:

$$CH_3COOH + NaHCO_3 \rightarrow CH_3COONa + CO_2 + H_2O$$

Based on this reaction, determine the role of sodium bicarbonate in the following diagram:

a) It is the excess reagent

b) React completely

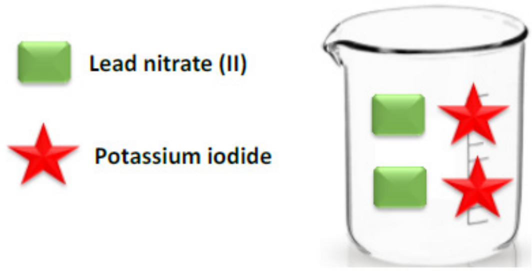
c) Sodium bicarbonate will remain unreacted

d) a and c are correct

4. When aqueous solutions of lead nitrate (II) and potassium iodide are mixed, a yellow precipitate of lead iodide (II) is produced according to the following chemical reaction:

$$Pb(NO_3)_2(aq) + KI(aq) \rightarrow PbI_2(s) + KNO_3(aq)$$

Based on this chemical equation determine the role of potassium iodide in the following diagram:



a) It is in stoichiometric proportions

b) It is the excess reagent

c) It is the limiting reagent

d) None of the above is correct

5. The combustion of pentane in the presence of gaseous oxygen occurs through the following chemical reaction:

$$C_5H_{12}(g) + 8O_2(g) \rightarrow 5CO_2(g) + 6H_2O(l)$$

When this reaction is carried out in an open system exposed to air, what is the limiting reagent?

a) The pentane

b) Oxygen

c) Carbon dioxide

d) Water

6. A chemical reaction occurs stoichiometrically when

a) Its components react exactly in the molar amounts of the adjusted chemical equation

b) There is no limiting reagent

c) There is no excess reagent

d) All of the above are correct

7. The performance of a chemical reaction responds to

a) The effectiveness of the synthesis process based on the excess reagent

b) The effectiveness of the synthesis process based on the limiting reagent

c) The effectiveness of the synthesis process based on the sum of all reagents

d) None of the above is correct

8. In the following chemical reaction, 5 moles of water were obtained from 20 moles of H_2 and 12 moles of O_2. The reaction yield was:

$$2H_2 + O_2 \rightarrow 2H_2O$$

a) 25 %

b) 41.7 %

c) 50 %

d) 20. 8 %

9. In the benzene sulfonation a yield of 50 % has been obtained for the product $C_6H_5SO_3H$. Abundant amounts of sulfuric acid have been used in the reaction, if 316.4 grams of $C_6H_5SO_3H$ have been obtained, what was the starting benzene mass?

$$C_6H_6 + H_2SO_4 \rightarrow C_6H_5SO_3H + H_2O$$

Molar masses:

Benzene: 78.1 g mol^{-1}

Sulfuric Acid: 98.1 g mol^{-1}

$C_6H_5SO_3H$: 158.2 g mol^{-1}

Water: 18 g mol^{-1}

a) The yield must be referred to sulfuric acid

b) 624.8 grams

c) 312.4 grams

d) 78.1 grams

10. Hydrochloric acid can be prepared by reacting sodium chloride and sulfuric acid according to the following chemical reaction:

$$NaCl(s) + H_2SO_4(l) \rightarrow HCl(aq) + Na_2SO_4(s)$$

If we start from 600 grams of sodium chloride and a 5 Molar solution of 5000 cm^3 of sulfuric acid. Determine reasonably:

Formula weight:

NaCl: 58.4 g mol^{-1}

H_2SO_4 98.1 g mol^{-1}

HCl 36.5 g mol^{-1}

Na_2SO_4 142.0 g mol^{-1}

a) Limiting reagent

b) Excess reagent. How much is left in grams or moles?

c) Amount of hydrochloric acid produced in grams or moles

d) Percent yield of the chemical reaction assuming that 300 grams of HCl have been obtained

Lesson supported by chemical demonstrations

The students' difficulties were worked out from the pre-test which was held during the week previous to the session with chemical demonstrations, which coincided with those collected in the bibliography (Wood and Breyfogle, 2006). These difficulties are basically summarized in that the students do not recognize that, previous to any stoichiometric calculation, the chemical reaction must be balanced, equal reactant masses will react completely in a chemical equation, the chemical reactants react according to the mass relationships found in a chemical equation and also that equal moles of reactants will react completely in a chemical reaction. Likewise, they also find it difficult to understand that the reaction products are obtained depending on the molar relationship with any of the reactants or the sum of them without taking into account the limiting reagent. Thanks to these data, the class focused on solving these difficulties beginning with a contextualization of the concepts of chemical reactivity. At this time a demonstration was used to clarify the concept of chemical reaction. Accordingly, these demonstrations aim to achieve an attractive and easily understandable representation of abstract concepts much unlike the way they have dealt with them in their regular classes.

Then, these students attended a class taught by the author including demonstrations in the chemistry laboratory of the school. It was divided into 4 parts, consisting of an introduction and contextualization of the concepts to revise, including a demonstration, followed by two problems of stoichiometry, limiting reagent and excess reagent and their corresponding demonstrations. These problems, in addition to the concepts mentioned above, contained the concept of reaction yields. Finally, some conclusions and clarifications were drawn. In this session, all the reagents used were safe and they were handled only by the teacher.

Post-test

After the new instruction with chemical demonstrations, the students were exposed to a new questionnaire similar in structure but containing some modifications in the questions. This was done in order that the memory of the pre-test not help them solve it, trying to use more deduction and understanding of the concepts than just the learning of definitions in a memoristic way.

This new questionnaire (post-test) was aimed to assess whether the difficulties and knowledge gaps in chemical reactivity had been worked out by the students. The questions asked in the post-test are included below together with a table showing the distribution of answers by the students and the correct answer in each case of the multi-choice options (Table 4). This questionnaire was complemented with a self-developed questionnaire for measuring the student's satisfaction with this type of methodology and two free - answer questions where they could express their feelings and assess the methodology of classroom demonstrations regarding its capacity to clarify and reinforce the concepts of chemical reactivity. The students were not given the answers of the tests nor the results in any case.

In the same way as with the pre-test, each 9 multi-choice options was assigned 1 mark each section of the problem 0.25 marks, amounting to a total of 1 mark, which made up for the maximum score of 10 marks for the pre-test. Each question was analyzed separately, thus outlining the difficulties of the students, in the same way as the problem that, in addition to the resolution strategies, reveals the errors in it.

Post-test of chemical reactivity concepts

1. Given the general chemical decomposition equation: A → B + C, where we must calculate the amount of product C formed in the reaction. What is the limiting reagent, if we start from 2 moles of A and get 1 mole of B and 1 mole of C?

a) B

b) A

c) C

d) Since there is only one reagent, this defines the efficiency of the process, without being limited by the quantity of another reagent

2. Urea synthesis can be carried out with lead cyanate and ammonia, as shown in the following chemical equation

$$Pb(NCO)_2(s) + 2NH_3(aq) + 2H_2O(l) \rightarrow Pb(OH)_2(s) + 2(NH_2)_2CO(s)$$

If we proceed with the reaction in aqueous medium with 4 moles of ammonia and 2 moles of lead cyanate, evaluate what the limiting reagent is

a) Water

b) Lead cyanate

c) Ammonia

d) It is stoichiometric

3. In a reaction type $3A + 8B \rightarrow 3AB_2 + 2B$ identify the limiting reagent

a) A

b) B

c) AB_2

d) None of the above is correct

4. The reaction of calcium carbonate with hydrochloric acid takes place as shown in the following chemical equation:

$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

Based on this reaction, determine the limiting reagent and how many moles of the excess reagent are left after the reaction is completed, if we start with 2 moles of $CaCO_3$ and 2 moles of HCl:

a) Limiting reagent $CaCO_3$; excess reagent HCl 1 mol

b) Limiting reagent $CaCO_3$; excess reagent $CaCO_3$ 1 mol

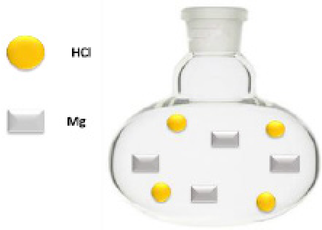
c) Limiting reagent HCl; excess reagent $CaCO_3$ 1 mol

d) Limiting reagent HCl; excess reagent HCl 1 mol

5. Magnesium reacts with hydrochloric acid forming magnesium chloride and hydrogen, according to the following equation:

$$Mg(s) + HCl(aq) \rightarrow MgCl_2(s) + H_2(g)$$

Based on this chemical equation determine the role of magnesium in the following diagram:



a) It is the excess reagent

b) It is the limiting reagent

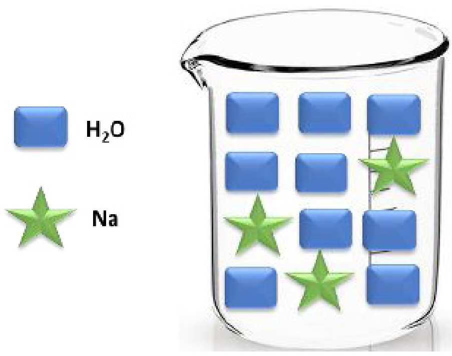
c) It is stoichiometric

d) The reaction does not occur due to excess hydrochloric acid

6. When sodium is brought into contact with water, a violent chemical reaction with release of hydrogen gas occurs, this chemical reaction is represented by the following equation:

$$Na(s) + H_2O(l) \rightarrow NaOH(s) + H_2(g)$$

Based on this chemical equation, determine the role of water in the following diagram:



a) It is in stoichiometric proportions

b) It is the excess reagent

c) It is the limiting reagent

d) None of the above is correct

7. Ammonia reacts with sulfuric acid to form ammonium sulphate. If in principle we have 2 moles of ammonia and 4 moles of sulfuric acid and 1 mole of ammonium sulphate is obtained, determine the reaction yield:

$$2NH_3(aq) + H_2SO_4(l) \rightarrow (NH_4)_2SO_4(s)$$

a) 50 %

b) 25 %

c) 100 %

d) It cannot be calculated

8. To determine the performance of PbI_2 in the following reaction, we must:

$$Pb(NO_3)_2(aq) + 2KI(aq) \rightarrow PbI_2(s) + 2KNO_3(aq)$$

a) Collect and isolate the precipitated lead iodide and evaluate the amount obtained with respect to the excess reagent

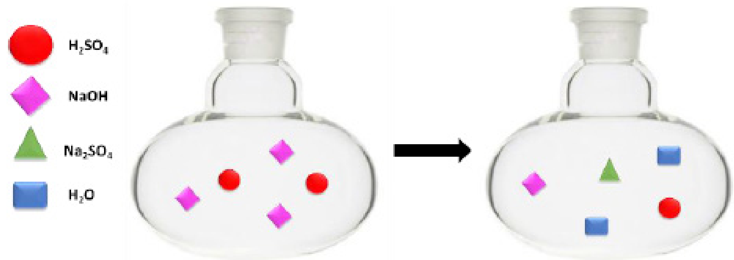
b) Collect and isolate lead iodide and evaluate the amount obtained with respect to the limiting reagent

c) It is not possible to carry out this experimental methodology

d) All of the above are incorrect

9. Sulfuric acid reacts with sodium hydroxide to give sodium sulphate and water, taking into account this reaction, determine the performance in the following diagram assuming there is no solvent

$$H_2SO_4 + NaOH \rightarrow Na_2SO_4 + H_2O$$



a) There has been no chemical reaction

b) 100 %

c) 50 %

d) 66.7 %

10. When calcium fluoride reacts with sulfuric acid, hydrofluoric acid and calcium sulphate are obtained as reaction products according to the following chemical equation:

$$CaF_2(s) + H_2SO_4(l) \rightarrow HF(aq) + CaSO_4(s)$$

If we start from a solution of 25 cm^3 of 5 Molar sulfuric acid and 500 grams of calcium fluoride. Determine reasonably:

Formula weight:

CaF_2: 78.1 g mol^{-1}

H_2SO_4 98.1 g mol^{-1}

HF 20.0 g mol^{-1}

$CaSO_4$ 136.1 g mol^{-1}

a) Limiting reagent

b) Excess reagent. How much is left in grams or moles?

c) Amount of hydrofluoric acid produced in grams or moles

d) Percent yield of the chemical reaction assuming that 2.5 grams of HF have been obtained

Interviews

Finally, in order to evaluate the feasibility of classroom demonstrations according to the teachers' point of view, all the science department teachers, consisting of 4 people (1 woman and 3 men between 39 and 63 years old) were submitted a semi-structured open response interview with questions about the methodology under study for approximately 30 minutes. Table 2 shows their characteristics.

Table 2: Description of the teachers interviewed.

Teacher	Teaching Experience	Academic Training	Subjects Taught	Tasks
Teacher 1	10 years	Chemical engineer	Mathematics, biology, physics and chemistry	Teacher
Teacher 2	30 years	Biologist	Biology, physics and chemistry	Teacher and laboratory manager
Teacher 3	30 years	Physicist	Mathematics, physics and chemistry	Teacher and laboratory manager
Teacher 4	42 years	Biochemistry PhD	Mathematics, biology, physics and chemistry	Teacher, director of the science department and head of studies of the school

The subsequent qualitative analysis of all interviews was carried out with the help of the Atlas.ti 7.5 software. A codification was used focused mainly on the opinion about the effectiveness, validity, valence, feasibility, need for prior work and time of chemistry instruction consumed for chemical demonstrations and the main limiters to implement it by teachers.

Description of the chemical demonstrations

The session consisted of four chemical demonstrations, including an introduction and contextualization at the beginning of the session and a conclusion and clarification time at the end. In the lesson, the topics that were taught were stoichiometry, limiting reagent, excess reagent and reaction yields. All reagents used were safe and were only manipulated by the instructor. During the lesson with chemical demonstration, the students were asked to act naturally as they normally would during a common lesson (i.e. paying attention, taking notes, asking questions, etc.).

First demonstration: dissolution of polystyrene in acetone (D-1): The objective of this demonstration was to clarify what is a chemical reaction. First, a one-meter polystyrene bar was immersed in a glass with 400 mL of water and the students were asked if there was a chemical reaction. After effectively seeing no reaction, the same polystyrene bar was submerged in 200 mL of acetone. Here, the polystyrene began to disappear while gas bubbles were emitted and the same question was asked to the students. At this time, the instructor explained that the polystyrene bar was dissolved in acetone given the non-polar character of both substances. The gas bubbles were not a newly generated product but the release of the air trapped in the polymer cavities, which therefore proved that there had been no reaction. Here, the instructor explained that if the polymer had been set on fire, the combustion reaction between polystyrene, which would be the limiting reagent, and the oxygen in the air would have produced carbon dioxide and water. After verifying that this was understood, the instructor presented the concepts of limiting reagent and excess reagent with two problems, insisting that once the chemical equation is described, before making any determination, the equation must be balanced.

Second demonstration: The reaction of eggshell carbonates and hydrochloric acid (D-2): 5.5. grams of a clean eggshell and half a litter of 2 M hydrochloric acid previously prepared was used. Considering that the eggshell is pure calcium carbonate, the balanced chemical equation that describes this reaction is

$$CaCO_3(s) + 2HCl(aq) \rightarrow CaCl_2(s) + CO_2(g) + H_2O(l)$$

The eggshell was kept submerged in hydrochloric acid with the help of a glass rod. This problem aimed to determine the limiting reagent ($CaCO_3$), the excess reagent (HCl) and how much is left over, as well as the amount of carbon dioxide (CO_2) produced based on the limiting reagent. Since this reaction took quite a long time, it was analyzed at the end of the session.

Third demonstration: The reaction between sodium bicarbonate and vinegar (D-3): One gram of sodium bicarbonate was placed in three beakers and vinegar was added in three stoichiometric proportions: 5.0mL, with sodium bicarbonate being the reagent in excess, 11.2mL, the reaction being found in stoichiometric proportions and 20.0mL with sodium bicarbonate being the limiting reagent. In the first case $NaHCO_3$ solid remained unreacted, while in the other two cases there was no unreacted solid. Calculations were performed to determine the limiting reagent in cases where it was feasible, the excess reagent and how much is left over, if it was appropriate. The balanced chemical equation that describes the process is

$$C_2H_4O_2(l) + NaHCO_3(s) \rightarrow NaC_2H_3O_2(s) + CO_2(g) + H_2O(l)$$

To qualitatively compare the amount of carbon dioxide produced in each of these stoichiometric proportions, the reaction was carried out in three Erlenmeyer flasks of 100mL capacity which were covered by three balloons with the three vinegar volumes in them from where the solid bicarbonate powder was dropped to assess how much the different proportions of CO_2 inflated the balloons. Those mixtures that were in stoichiometric proportions and where the $NaHCO_3$ was the limiting reagent produced the same amount of CO_2 and therefore the balloons were inflated to the same volume. However, the balloon where the bicarbonate was the excess reagent was less inflated, because the amount of CO_2 produced was lower. Calculations of the amount of CO_2 produced, in each case were performed and compared with the balloon's size. Finally, this effect was also qualitatively assessed by placing 1 drop of a detergent solution in three 250mL graduated cylinders with 1.0g of $NaHCO_3$ and the three vinegar volumes and evaluating on the graduating marks the height of the detergent foam during the reaction on the graduating marks. The elevation was approximately equal in the case of stoichiometric proportions and where the limiting reagent was $NaHCO_3$, and much lower, where $NaHCO_3$ was the excess reagent.

Fourth demonstration: Lead iodide precipitation (D-4): 150mL of a 0.1M solution of lead nitrate (II) was poured over 350 mL of another 0.1 M solution of potassium iodide, producing a yellow precipitate (reaction known as gold or yellow rain) of lead iodide. The balanced chemical equation that describes the process is

$$Pb(NO_3)_2(aq) + 2KI(aq) \rightarrow PbI_2(s) + 2KNO_3(aq)$$

Subsequently, the limiting reagent, the excess reagent and its amount was determined. The amount of lead iodide produced based on the limiting reagent (theoretical yield) was then calculated and compared with the amount obtained prior the session by the instructor after mixing the same quantities and isolating, washing and drying the obtained product (experimental yield). Based on these two data, the percentage yield of the reaction was calculated.

Results

Multi-choice pre-test

Participating students obtained an average grade of 5.81 out of 10 in the pre-test. The 9 multiple-answer questions and the problem with 4 sections were considered, where each of these was valued at 0.25 marks based on a correct and well-based answer. The same group of students obtained a significantly better score in the post-test, evaluated in the same way, with a score of 6.25. 56.3 % (9 students) of the participating students increased their score between both tests. 6.3 % (1 student) of the participating students did not see any change in their score and 37.5 % (6 students) of the students decreased their score. The multi-choice questions of both tests were made as modifications of others taken from the literature [15,36-38] as well as the problems [39], adapted to the difficulties of Spanish students on the subject of our research.

In the pre-test, question 1 was focused on the steps to be followed when solving a stoichiometry problem. Specifically, the first one that allows us to establish stoichiometric relationships. In this case, only 31.3 % of the students answered correctly. The others erred and showed that they had not understood the pathways of stoichiometry.

Questions 2 and 6 were referred to the excess reagent, its relationship with the limiting reagent as well as to the stoichiometric proportion conditions. In question 2, 93.8 % of the students answered correctly. In question 6, 93.8 % of the students also got it right, demonstrating that they had understood these relationships with the traditional explanation they had received.

Question 3 aimed to determine if students understood the concept of limiting reagent and its implication in a chemical reaction. In this case, 81.3 % of the students responded correctly, so they got to grasp that when this reagent has reacted completely, the reaction stops.

Question 4 reflects on a very common mistake: the importance of stoichiometric balance and the meanings of coefficients and subscripts in chemical reactions [5]. Here, only 18.8 % of the students made a correct deduction from the situation. The biggest mistake was due to the consideration that chemical reactions take place in equimolar, amounting to 31.3 %.

Question 5 is about whether the student is able to extrapolate the knowledge of stoichiometry and limiting reagent to a daily situation, outside the laboratory. It is a combustion reaction where the excess reagent is the oxygen in the air itself. In this case, 68.8 % of the students responded correctly, interpreting that the stoichiometric proportion of the burning hydrocarbon is lower than the oxygen in the air. However, 31.3 % interpreted that the oxygen would run out before the hydrocarbon.

Questions 7 and 8 were about the reaction yield and its calculation on the basis of the limiting reagent. In this case, 37.5 % of the students answered correctly to question 7, showing great confusion. They assume that all reagents contribute equally to the reaction yield, and that the yield is a calculation based on the sum of the amounts of all reactants involved in the process, 37.5 %. In question 8, 50 % of the students answered correctly, considering the stoichiometric proportion, the biggest mistake was not considering the limiting reagent 12.5 %, or the stoichiometric proportions 37.5 %.

Question 9 included a calculation in which the student should consider the concepts of stoichiometric proportions, unit changes, limiting reagents and percentage performance. In the pre-test, the percentage of students who answered this question correctly was 56.3 %, so the biggest errors 31.3 % are due to considering that chemical reactions take place in mass relationships found in chemical reactions. These results are tabulated in Table 3.

Table 3: Distribution of student responses in the pre-test multi-answer questions.

Question	Answer				
	a	b	c	d	No answer
1	0	**7**	0	12	0
2	0	1	**18**	0	0
3	0	3	1	**15**	0
4	6	4	**4**	5	0
5	**12**	5	2	0	0
6	1	0	1	**17**	0
7	1	**7**	7	5	0
8	**11**	2	4	2	0
9	1	5	**11**	2	0

Note: The correct answers are shown in bold.

Pre-test numerical problem

The pre-test contained a problem with four sections that included the information of one of the reactants in terms of volume of a known concentration aqueous solution and a second reactant, with its amount expressed as mass of a solid reagent. In addition to this, the chemical equation needed to be adjusted before stoichiometric calculations.

In the first section, the identity of the limiting reagent was reasonably determined. 62.5 % of the students answered this question correctly. For this they used the first principles of the stoichiometry of the chemical reaction, that is, they established the minimum amount of each reactant needed to react with the other reactant, so it should be consumed completely, but not the other one. Most of these students established relationships based on moles. However, two of them opted for establishing mass relationships between the reactants in the equation to find the limiting reagent.

The second section required to identify the excess reagent and establish the amount of the reagent that had not participated in the chemical reaction. Only 25 % of the students knew how to answer this section. It seems clear to them that the excess reagent is the one that is not the limiting reagent. However, it does not seem so clear to them that the amount that remains unreacted in the system is equivalent to the difference between the initial amount and the one that has played a role in the chemical reaction.

The third of the sections required to calculate the amount of one of the products formed. 50 % of the students knew how to answer this question. The biggest mistakes were to consider that the reaction took place in mass relations or to mix molar relations with mass relations under the same equality. Finally, they were asked to determine the percentage yield of the foresaid reaction departing from a given mass amount obtained from the reaction. Here, where the maximum number of successful students should be, at most, those who answered well the previous section, 37.5 % adequately resolved the issue. The errors found in this section were due to not knowing the definition of percentage yield or to problems with the unit changes from grams to moles and vice versa.

Multi-choice post-test

Thus, the first and third questions of the post-test intend that the student know how to identify the limiting reagent and its relationship with the other reactants present in the chemical equation. Here 87.5 % of the participating students responded correctly to question 1. while 50 % of the students responded well to question 3. In this case, the biggest mistake lies in the lack of consideration that a substance that is in excess, once the chemical reaction is over, is still present in the system and can be represented in a general equation.

Question 2 aims to clarify whether students have resolved their doubts about the stoichiometric ratio. 62.5 % of students responded correctly. Their biggest errors are due to not considering stoichiometric coefficients and their significance: 31.3 %.

Question 4 requires to know how the reactants are related to each other, the limiting reagent and the excess reagent. 62.5 % answered this question correctly. The most common errors were due to not considering the stoichiometric ratios 18.8 %, nor the reactant ratios between them: 18.8 %.

Question 5 asked about the importance of stoichiometric balance and the meanings of coefficients and subscripts in chemical reactions. Here, only 21.1 % of the students made a correct deduction from the situation. The biggest mistake was due to the consideration that chemical reactions take place in equimolar amounts: 31.6 %.

Question 6 and question 8 refer to the students' knowledge about the limiting reagent, excess reagents and reaction yields and their application to real situations outside the classroom. In question 6 the percentage of successes was 93.8 % and, in question 8, it was 68.8 %. The most remarkable error corresponded to attributing to the excess reagent the function of the limiting reagent.

Question 7 deals with the reaction yield and its calculation. In this case, the success rate was 37.5 %. The highest percentage of error was due to not considering the stoichiometric ratios 25 %, or the limiting reagent 18.8 %.

Question 9 requires a knowledge of the concepts of stoichiometric balance, stoichiometric proportions, limiting reagent and percentage yield. In this case, the percentage of successes was 43.8 %. The greatest errors occurred in not considering that the substances that have not reacted continue to be part of the system. 25 %, do not consider the stoichiometric proportions 18.7 %, or disregard the limiting reagent and its relationship with the other components of the chemical equation 12.5 %. These results are tabulated in Table 4.

Table 4: Distribution of student responses in the multi-answer post-test questions.

Question	Answer				
	a	b	c	d	No answer
1	1	0	1	**14**	0
2	1	5	0	**10**	0
3	**8**	0	1	7	0
4	3	3	**10**	0	0
5	**9**	3	4	0	0
6	1	**15**	0	0	0
7	4	3	**6**	2	1
8	3	**11**	0	2	0
9	4	3	2	**7**	0

Note: The correct answers are shown in bold.

Post-test numerical problem

The post-test contained a problem with the same structure as the pre-tests. This had four sections and the information of one of the reactants in terms of volume of a known concentration aqueous solution and a second reactant, whose amount was expressed as mass of a solid reagent. As in the previous case, the chemical equation needed to be balanced before stoichiometric calculations.

In the first section, the identity of the limiting reagent was reasonably well determined. This question was answered correctly by 68.8 % of the students using the same procedures as in the pre-test and operating mostly with molar relationships. Only one student preferred to establish mass relationships between the reactants to determine the identity of the limiting reagent. The second section required to identify the limiting reagent and establish the amount of the reagent that had not participated in the chemical reaction. This time, 50 % of the students responded adequately to this section. Now, they not only know that the excess reagent is one that is not the limiting reagent, but they also know how to calculate the amount of reactant that does not participate in the reaction. Even so, several students made some basic miscalculations that invalidated the results, despite having established the relationship well.

The third of the sections required to calculate the quantity of one of the products formed. 43.8 % of the students knew how to answer this question where the most striking mistake continued to be to mix molar relationships with mass relationships under the same equality. Finally, they were asked to determine a percentage yield of a said reaction based on a quantity of mass obtained from the reaction. 37.5 % adequately solved the issue. The errors found in this section were due to calculation errors dragged from the first section of the problem and in a single case due to not knowing the definition of percentage yield.

Electroencephalic analysis

Table 5 presents the emotion measurements from the electroencephalography analysis performed for the two selected students during the lesson with chemical demonstrations and the respective written self-assessment.

The values represent the average relative emotional level (in percentage) in relation to the levels experienced during the session by the subject; in this sense, 100% would represent the highest and 0% the lowest emotional level experienced during the session by the subject. Within these parameters a high degree of interest during the lesson and a very low degree of stress were recorded. Also, reduced degrees of relaxation and focus and average degrees of engagement and excitement were found. Within these parameters a modest value of interest for the session was found [29,40]. Furthermore, low values of focus and relaxation are also shown. Table 4 also shows the data that these two students have filled in a table evaluating each of these emotions during the lesson with demonstrations. These data reflect that student consider the session with chemical demonstrations more intense in sensations than the EEG values show (Table 5).

Table 5: Students' EEG measurements and self-concept of their emotions during the class with demonstrations.

Student		Engagement (%)	Excitement (%)	Interest (%)	Relaxation (%)	Stress (%)	Focus (%)
Student 1	EEG	56	55	99	33	5	30
	Self-assessment	100	100	100	75	15	100
Student 2	EEG	58	45	97	27	13	24
	Self-assessment	100	100	100	30	15	60

Electrodermal activity analysis

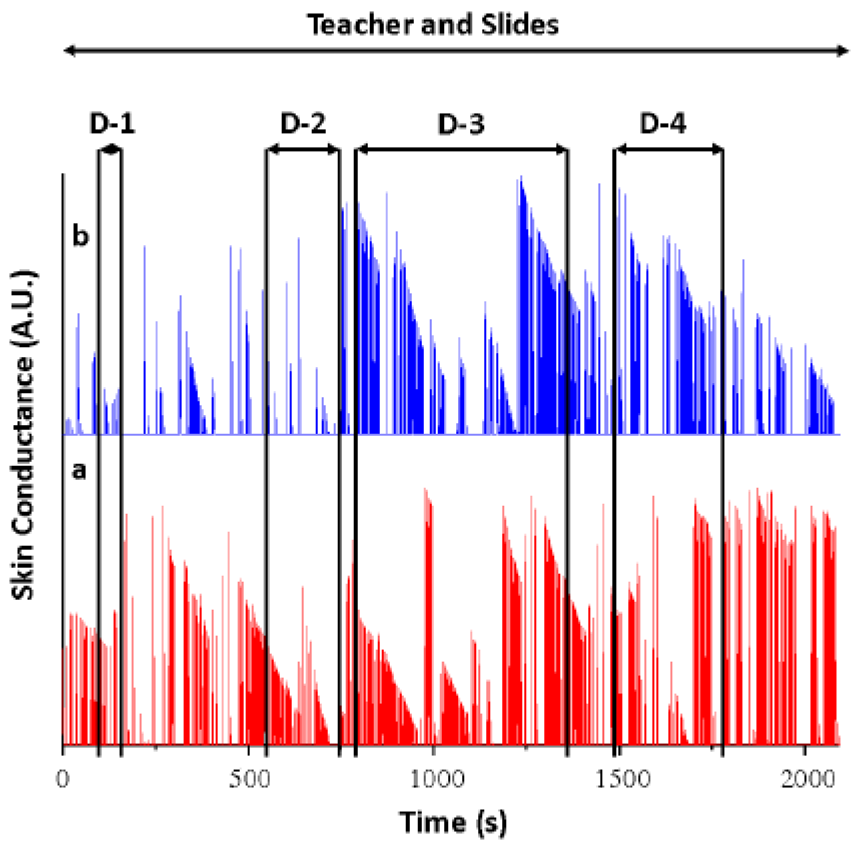


Figure 2: Electrodermal activity recordings of the
a) female student
b) and male student
Conductance measures were taken continuously during the lesson development with chemical demonstrations. The figure shows the time taken by each demonstration (D) and the teacher and slide time, which corresponds to the total duration of the session.

Figure 2 shows the electrodermal activity (EDA) signals recorded during the lesson from the selected students. EDA allows for the monitoring of the emotional and/or cognitive processes that the students showed during the session with chemical demonstrations.

The highest relative conductance value of the skin (99 %) for the female volunteer (Figure 2a) occurred during the explanation of the D-3 regarding the determination of the limiting reagent and the excess reagent in the three proportions used for the assay (Figure 2a). This student showed a large set of prolonged psychophysiological responses of high relative intensity (98 % - 90 %) and amplitude that are mostly occurring during the D-4, the precipitation of lead iodide and its explanation. The remaining signals within this group belong to the D-3 and to the conclusions of the class, in which the student actively participated. The rest of the physical responses recorded in the student's EDA belonged to the D-4 and their interaction with the teacher (Figure 2a). The skin's conductance reached its maximum value for the male participant (Figure 2b) in a phasic response during the D-3 with a value of 99 %. In addition, as can be seen in Figure 2b, another large set of values that show high relative percentages of conductance (98 % - 91 %) where the vast majority of them are due to D-3, the reaction of sodium bicarbonate and vinegar. Additionally, this was the longest, given that it included three different ways of visualizing the reaction process (Figure 2b). The rest of this group of signals are occurring during the D-2 and D-4 and the stress generated from the cognitive effort necessary to understand the explanation of the phenomena that develop inside them. The rest of the psychophysiological responses are always related to the four demonstrations and the interaction of the student with the teacher in their explanation.

Eye-tracking analysis

Table 6 shows the eye-tracking parameters recorded during the lesson using chemical demonstrations. These parameters were previously defined in the methodology section. Figure 2 presents an example of fixations with a green mark, showing the point of view of the students during different stages of the session.

Table 6: Different indicators of eye movements for a lesson with chemical demonstrations.

Area of Interest		Total Fixation Duration (s)	Stage Duration (s)	Percentage of Fixation (%)	Number of Fixations	Fixation per Second	Reviews
D-1	Student-1	36.96	61	60.6	93.94	1.54	20.39
	Student-2	34.64	61	56.79	89.85	1.47	19.53
D-2	Student-1	15.34	204	7.52	44.24	0.22	22.83
	Student-2	10.7	204	5.25	33.86	0.17	20.01
D-3	Student-1	43.59	570	7.65	136.24	0.24	67.04
	Student-2	26.77	570	4.7	89.52	0.16	48.64
D-4	Student-1	51.7	294	17.59	155.91	0.53	72.77
	Student-2	45.74	294	15.56	135.5	0.46	62.01
Teacher	Student-1	734.55	2162	33.98	1982.6	0.92	562.4
	Student-2	658.16	2162	30.44	1825.81	0.84	523.75
Slides	Student-1	296.32	2162	13.71	928.08	0.43	325.04
	Student-2	222.41	2162	10.29	709.87	0.33	271.11

During D-1 a high value of the fixation time, fixations per second and a very low number of revisions were recorded. However, D-2 did not produce so much eye-catching attraction (Table 6). Similar values were found for D-3 (Table 6), this being the longest of all consisting of three different parts that divert the attention from the Areas of Interest. In addition, these three parts happen quickly due to the reaction kinetics between sodium bicarbonate with acetic acid, which makes the intermediate explanation longer than the demonstration itself, decreases fixation values per second and the reviews associated with it. Otherwise, high values of fixations per second and a low number of reviews registered during D-4 are shown (Table 6).

Finally, these values can be compared with the data obtained from the other two Areas of Interest. The teacher (Table 6) gathers the highest values of eye-tracking analysis during the instruction in accordance with the eye-catching record, followed by the demonstrations and the blackboard (slides), based on the number of fixations per second and the revisions of Areas of Interest. Figure 3 shows four representative examples of student fixations, registered with the eye-tracking system, during instruction with demonstrations. In Figure 3a, a fixation is shown in the figure of the teacher. Figures 3b-3d show the fixation on three moments of the demonstrations made.

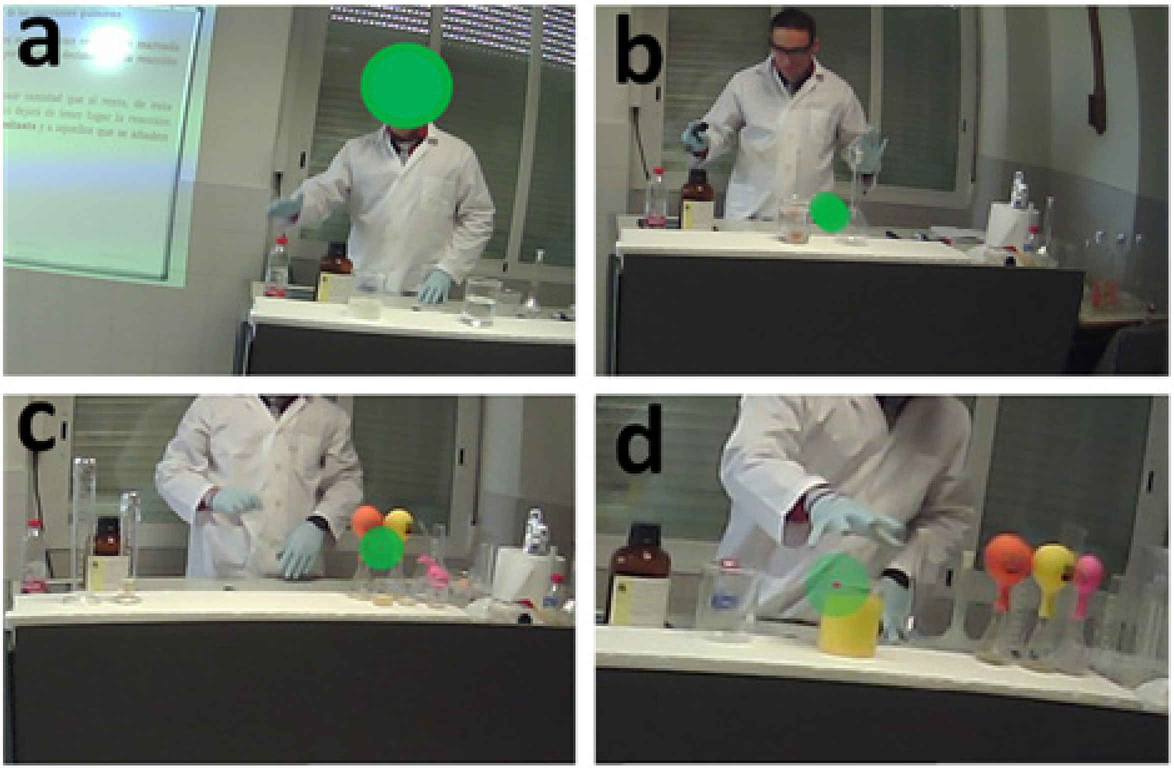


Figure 3: Eye-tracking selected images of the students in the lesson with demonstrations. The green spot marks a fixation of a point of view on a specific Area of Interest. As stated above, three Areas of Interest were defined here: (1) The demonstration objects, (2) the instructional support slides and (3) the teacher. In the figure,

a) teacher

b) D-2

c) D-3 balloons filled by CO_2 emission from different proportions of $NaHCO_3$ and vinegar

d) D-4, PbI_2 precipitation. Every image corresponds to a different stage of the lesson

Neuroqualitative survey

According to the neuroqualitative interviews, both students recognized that this methodology of classroom demonstrations is very eye-catching and contributes to maintaining attention, which can be translated into a better assimilation of the concepts, worked for them. Here a student expressed that *"it is less tempting to lose concentration"* and both believe that it is entertaining. Furthermore, they thought that this would achieve a better long-term memory of the taught items. *"In the long term, it is clear to me that I will remember the lessons with demonstrations better than the traditional ones, because it is much more visual. Personally, I have visual memory, so practicing, being able to experiment, I think it is much easier to remember these kinds of sessions for a longer time."*

Despite this, one of these students recognized that this methodology should be supported by other teaching methodologies, including, for example, a pre-class and a post-class work and not only the class with chemical demonstrations to really offer a positive effect. *"I believe that in order to achieve a really effective learning it is necessary, in addition to the use of demonstrations, a previous and a subsequent work, as well as a continuous practice of theoretical exercises."* This student also admitted that the effectiveness of the method lies strongly in the way to apply it, just as a good regular class can be unforgettable, a class with demonstrations can be a disaster if it is not carried out properly, the student said: *"When someone communicates something with enthusiasm, you learn so much more, because you see that the other person is getting involved".* The two students agreed that the most important concept revised in the class was the concept of stoichiometric proportion, since it establishes the way in which chemical substances, both reactants and products, behave among themselves, when they are part of a chemical reaction. *"stoichiometric proportions, because they are the basis for the relations between reactants."* Finally, both students admitted that the demonstration that most caught their attention was the precipitation of lead iodide (D-4). While the students described this demonstration, the phasic response of the EDA recorded an intense signal due to a moment of emotional truth (Figure 4). One of the students commented that *"in the reaction of lead nitrate and potassium iodide, you did not expect that the mixture of two colorless liquids that looked like water had a product of a completely different color and also that the change was so instantaneous"*.

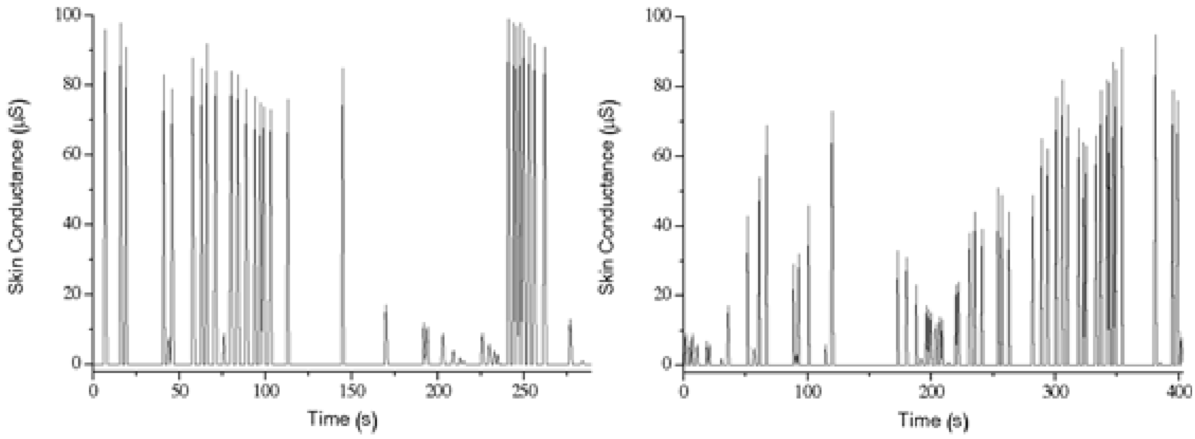


Figure 4: Electrodermal response of the male (a) and female (b) students during the interview.

Survey for the assessment of methodology

In class, the learning environment that surrounds students, such as curriculum, teacher education and student interaction influence the students' motivation in learning science [41]. Considering these aspects, we have developed a small questionnaire to gather the opinions of the students regarding the methodology they have experienced. This questionnaire had two parts, one in which the methodology was evaluated as such from a personal point of view (Table 7) and a second part where they expressed how they have felt during the class with chemical demonstrations (Table 8). These questions sought to obtain an assessment of the methodology of chemical demonstrations and a comparison with the same contents taught with traditional lecture-based classes, video viewing and the resolution of numerical problems on the board. These results are consistent with others already found in the bibliography [24], where it is generally appreciated that the majority of students are positioned in firm agreement with the use of chemical demonstrations to work on the didactic units of the chemistry course curriculum (Table 7). Students considered that this methodology is useful to reinforce the concepts previously seen in class as far as it helps to hold the students' attention and it is more effective emotionally. They also consider that it should be used more frequently (Table 8).

Table 7: Results of the assessment survey of the chemical demonstration methodology.

Affirmations	Strongly disagree (%/students)	Disagree (%/ students)	Neither agree nor disagree (%/students)	Agree (%/ students)	Totally agree (%/students)
I have found it useful to reinforce the concepts of chemical reactivity through the demonstrations carried out in the classroom.	0/0	0/0	18.75/3	31.25/5	50/8
I consider that this session has proved more useful than traditional chemistry classes.	0/0	0/0	25/4	37.5/6	37.5/6
This methodology is entertaining and less boring than the traditional methodology in chemistry classes.	0/0	0/0	0/0	18.75/3	81.25/13
I consider the chemical demonstration methodology more effective than watching videos to review the concepts of chemical reactivity.	6.25/1	6.25/1	18.75/3	18.75/3	50/8
This methodology has helped me keep my attention on the proposed topic.	0/0	0/0	12.5/2	37.5/6	50/8
I think it would be helpful to address a higher percentage of the chemistry classes with this methodology.	0/0	0/0	12.5/2	43.75/7	43.75/7

Results of the assessment survey of the chemical demonstration methodology

The elements were constituted using 5-point Likert scales. The elements of the first part of the questionnaire were attributed to the following qualifications 1 = totally disagree, 2 = disagree, 3 = neither agree nor disagree, 4 = agree, 5 = totally agree. The elements of the second part of the questionnaire took the following qualifiers 1 = very low, 2 = low, 3 = neither high nor low, 4 = high, 5 = very high.

Students consider that during the class with chemical demonstrations their affective perception of the class measured in terms of engagement, excitement, interest, relaxation and focus has been mostly between high and very high, with some students who have not given a clear opinion marking neither high nor low. In these options, only one student marked the option of a low level of relaxation, in the others this response was not recorded, indicating mostly positive feelings (Table 8).

Table 8: Self-assessment of the students' feelings during the lesson with chemical demonstrations.

Feeling	Very Low (%/Students)	Low (%/Students)	Neither High Nor Low (%/Students)	High (%/Students)	Very High (%/Students)
During this session my level of engagement has been	0/0	0/0	18.75/3	50/8	31.25/5
During this session my level of excitement has been	0/0	0/0	25/4	37.5/6	37.5/6
During this session my level of interest has been	0/0	0/0	6.25/1	37.5/6	56.25/9
During this session my level of relaxation has been	0/0	6.25/1	25/4	37.5/6	31.25/5
During this session my level of stress has been	56.25/9	31.25/5	6.25/1	0/0	6.25/1
During this session my level of focus has been	0/0	0/0	25/4	50/8	25/4

Self-assessment of the students' feelings during the lesson with chemical demonstrations

We estimate that the students did not know the formal definition of these terms, so perhaps they should have marked lower values in relaxation and focus. Regarding the stress level, we found that most of the students felt that it was low and very low, one student offered no opinion and another considered that it had been very high (Table 8).

Open-response questionnaire to students

Along with this test, the students were provided an open response questionnaire in order to express their opinion about the teaching methodology based on chemical demonstrations and thus establish the points in favor and against which they found in it. The opinion of the students is positioned robustly in favor of the use of this methodology. In general, they emphasize that it makes the class more interesting, that it helps strongly to maintain attention. Here a student expressed that *"I like that it is interactive and dynamic, it also captures the student's attention"* and practically everyone believes that it is entertaining. A large number of students were in favor of the fact that it is different. Here a student pointed out *"I like it because it is different from what we are used to".* Many of them highlight interactivity. They consider that using this methodology they feel they have the leading role in the sessions, although a student indicated that he would have liked to be able to make the experiments. 75% of the students think that attending classes with demonstrations they would achieve a better assimilation of the concepts, and even some students pointed out that this allows them to check what they have seen in theory with real examples. They also believe that these kinds of classes would help them retain information better and for longer.

All of them have pointed out as a positive value the fact that these kinds of classes are *"very visual"*, which makes them more attractive. Several students not only think that chemical demonstrations should be used more often in chemistry, but that they should be used in many other subjects. Here one student pointed out that if they were extended to the point that they were normal it would be difficult to control the seriousness. Another student states that perhaps it would be difficult to hold attention to a similar degree during the explanation. Half of the students consider this type of classes as complementary since they intensely reinforce knowledge. They also acknowledge that, without the previous work from their lecture-based classes and later as problem-solving classes, they could not have fully understood the contents concerned. They think that, in demonstration-based classes, the calculation of the problems is too fast for them to assimilate without previous work. Some of them believe that the problem may be more work for the teacher (1 student), greater need for resources (1 student) and that it requires a lot of time (5 students) although they all claim that it is still worth it. We would like to summarize this part of the study with the opinion of one of the students who said textually: *"This methodology seems very interesting to me since it has allowed me to discover with the experiments, what would happen if the exam problems became a reality, which I liked, since it has allowed me to explore the subject deeper and it has taught me how to approach the stoichiometric problems with more enthusiasm and imagination".*

Open response semi-structured interview for the teaching staff

With the main purpose of evaluating the viability of the use of classroom demonstrations, the teachers from the science department in the school responsible for the area of physics and chemistry were interviewed about this methodology. This department is composed of 4 teachers all of them with a long teaching career ranging from 10 to 42 years in the school. All of them receive updated training on new tools and methodologies during the months that classes finish in high school. In fact, one of them acknowledges that *"the school is grateful that the teachers are trained".* However, they assume that no training related to laboratories is received, which reflects that the use of classroom demonstrations is not promoted at least in basic education in Spain, as the companies that offer this training cover much of the National territory. All of them insist that they try to combine different teaching methodologies, whether supported by new technologies such as the iPad, problem-based learning, development of thinking skills and constructivist methodology. However, they admit that the one they use the most is the lecture class and they consider that this cannot be lost, that the teacher has to *"direct what the student is doing".* However, teachers recognize that the most efficient way to instruct students is that in which *"the student gets involved and feels in charge"*. That is, a corporativism in which the student is not a mere spectator, but rather plays a role in the classroom and in the development of the instruction.

All teachers know or have heard about classroom demonstrations. Some of them even say that they have used it on occasion to contextualize a practical class or explain the practice before students do it. In this sense, everyone considers that they should not replace laboratory practices, which can and should both coexist, since *"if the teacher becomes the only actor in the experimentation, I think we would be making a little mistake"*. If that were the case maybe we would be having regular classes again, only with live visual support. Another of the teachers argues that students should also engage in laboratory work because *"knowing how to be in a laboratory for a researcher, for a scientist is very important. Hands-on training in the laboratory means everything: how to handle the chemicals, the precautions that you have to take, safety measures. All of that will come in handy at University if they have had previous experience and they will also miss it if they have never had it"*. The teachers have agreed that this methodology is very interesting for students because they have a better time and they can visualize what they are studying, a fundamental aspect given the abstraction degree of chemistry. It also attracts them and surprises them a lot *"you only have to remember when you were a student"* teacher remarks that such experiences you will never forget and, above all, the students understand the lessons so much better. Another of them points out that if the activity is well designed *"then it would allow you to ask the students what they have learned and what they liked the most, what they liked the least as well as to obtain feedback and improve the experiment".*

Despite the widespread opinion that chemical demonstrations are really useful, everyone affirms and reiterates during the interview that the great time is the great limiting agent, as most teachers only have so many hours to comply with the official syllabus This forces them to dismiss the sessions that take longer to complete. They also point out that students must be prepared for the University admission exams, for which they must comply with a series of learning objectives and strategies for responding to the exam questions which do not allow for leaving the marked path. Other limiters are also pointed out such as the amount of time and work it takes to prepare this type of session, to verify which resources are available as it is the teachers in the science department who are responsible for maintaining the laboratories, verifying that everything works. A poorly performed demonstration is counterproductive for students since it leads to misunderstandings, confusion, lack of attention, boredom of the students and so on. So, they admit that it is not so easy to take an essay from a database or another partner without having tried everything beforehand, that the experiments have to adapt well to the contents that are intended to work, check the safety conditions such as avoiding the emission of toxic gases, explosions, waste treatment, ...

One of the teachers points out that this type of experience is more comfortable and fruitful with smaller groups. Another one indicates that it also depends on the group of students and the predisposition that they show towards this type of session. One of the teachers makes self-criticism by commenting that his lack of training in chemistry prevents him from carrying out this type of experience because he does not feel confident with the laboratory material. As concerns the previous remark, teachers are divided regarding the ability of the teaching staff to teach properly using this type of tools Another member of the teaching staff comments that she does not consider taking on this task in her classes because of the lack of time and that she is the only one who does not do any laboratory practice with the students, but recognizes that all her colleagues could do it perfectly Only one of them thinks the opposite of the other teachers because he believes that *"a good teacher is a good communicator, a good leader, then moving on to the branch of chemistry I have met few good chemistry teachers, I think chemistry because of its degree of abstraction, I think to find the right way for the student to perceive the fundamental concepts and apply them concretely, It is very difficult"*. This extends to the use of demonstrations by other teachers. Here everyone points out that they would love more feasibility to develop this methodology where the main limiter is the time they have.

We have asked them to suggest some measures which should help to implement this methodology. Here they think that since the use of demonstrations can be very beneficial, it would not be hard to encourage other teachers to use them. They argue that if teachers saw a class like this live, they would realize the potential of this type of session, given that it is a way for students to verify that the teacher also enjoys it and motivates them to study the subject. The first thing they think should be done is to introduce this type of session into the course's schedule. Here they also believe that the laboratory should be a comfortable place with good visibility of the students towards what the teacher does. And, most importantly, a database will be provided where they can clearly inform themselves of all the aspects to consider when carrying out a good demonstration. They even quote the publishers responsible for generating the school's material who could help disseminate this material easily and in Spanish. As we know, there are several texts dedicated to classroom demonstrations such as those of Shakhashiri [22], among others, but their promotion in Spain is very low as teachers make us see. Also, going a bit further into the difficulty of the time factor, they consider that they could offer demonstrations such as video tutorials so that they could work under the flipped classroom model. Although they consider that much of the power of this methodology lies in the staging and the fact that it takes place in front of the students' eyes. Accordingly, the video could lower its effectiveness, which is consistent with previous studies [24] and the opinion of the students themselves (Table 7).

They firmly believe that there should be a subject that covers all experimental work and thus all teaching methodologies could be tackled without abandoning the training of any specific skills. However, they argue that chemical demonstrations, laboratory practices and all experimental aspects required by the scientific training of students has to be done in coordination with the subjects in which the mainstream in-class theory and problem solving sessions are done. A teacher believes that *"there has to be a person who is in charge of the laboratories, a person who really has all his full schedule and his full day in this because there is a lot of hard work to do, from having everything absolutely inventoried, all registered, any type of incident registered, material that has been used or broken, damaged reagent or many other circumstances, including cleaning and material provision for the students. It is not only us performing the practice but having the students performing it too."*.

Discussion

Analysis of the results of knowledge tests

In our population under study, we have found that students have great problems for understanding and interpreting the concepts of stoichiometry and limiting reagent, despite knowing how to solve type problems, which is supported by many previous studies [7,36,37]. Despite the short time we have had to correct the misunderstandings of students, we have managed to understand the value of stoichiometric proportions and begin by balancing a chemical equation before making any determination. We have also achieved an improvement in the understanding of the identification and importance of the limiting reagent in subsequent determinations. Other authors point out that a common difficulty with the concepts of limiting reagent is the consideration that the same substance acts as a limiting reagent regardless of the scenario [7,38]. We have clarified this fact, where the limiting reagent depends on the quantities of each of the reactants that are available for a specific chemical reaction with the third demonstration, where sodium bicarbonate and acetic acid were in three different stoichiometric proportions adopting different roles.

Conceptually, where we have encountered more difficulties is in the reaction yields in the pre-test, with a slight improvement in the post-test. Perhaps this could have been improved to a greater degree by introducing some other demonstration where reaction yield was considered and not only in the fourth demonstration. A very interesting misunderstanding that we have identified in this study is the fact that students consider that substances that have not reacted completely must disappear from the reaction medium automatically. This is also seen in the second section of the problems, where knowing how to identify the excess reagent and determine the excess amount of it has become a difficult issue for the students most of whom have improved considerably after the instruction from the point of view of calculation. However, as seen in the questions with multiple choice answers, under a conceptual point of view, the remaining reagent does not become well assumed by them. Maybe, more time should have been devoted to reinforcing it with an example.

In the problems we found that all the students attempted them and did not leave them blank. After balancing the given chemical equation and determining the number of moles or grams in some cases of the reactants from the concentration data of solutions and mass quantities, they know how to identify the limiting reagent from the first principles using the stoichiometric proportions to elucidate which one would be depleted in the first place, thus resulting in the chemical equation not continuing to progress. As for the identification of the excess reagent, all these students have been able to elucidate it since they are aware that it is the reactant that does not limit the reaction. However, the confusion consisting of the fact that the amount of reagent that does not participate in the reaction disappears immediately, causes these students to fail to give a correct answer to this section in the pre-test. However, after the instruction, this calculation problem seems to have been solved in the post-test, but not the conceptual problem.

As for establishing the relationship between the quantities of products formed on the basis of the limiting reagent, this seems to be another section in which students know how to develop a model-problem. We find two striking errors here. In the first place, we had a student who in both tests mixed the molar quantities with the mass quantities under the same equality despite having established the proportion well. The other student failed this section in the post-test because he made a mistake in the calculation of the amount of excess reagent that reacted. In this case it was a miscalculation, not a misunderstanding of concepts. Using this amount to establish the relationship came from the previous error, which could have been avoided by using the limiting reagent to establish the relationship directly. In the fourth section, clear errors were observed in the pre-test due to the ignorance of the concepts of reaction yields. However, in the post-test, it seems clear that these concepts have taken hold after the instruction. Many errors were detected due to miscalculation in the previous sections, which made wrong the amounts previously calculated and which they should subsequently use to establish the reaction yields.

Electroencephalography

According to the results of the EEG (Table 5), students present high values of interest during this teaching methodology and very low stress, which reveals a strong affinity for the methodology developed in the session. This parameter is essential for the attention level [27]. The low value of stress could be explained by the comfort of students with this learning methodology and indicates that it can stimulate greater student productivity in the class. These two parameters cooperate in the acquisition of knowledge and complacency for learning and assimilation of information along with the application of the approach [27,28]. On the other hand, the low value of focus is attributed to the large number of stimuli that students receive in class with demonstrations, which means that attention is not fixed on a single activity during the demonstrations. Relaxation also shows a reduced value, possibly due to the involvement in the session, which demands for their participation in the instruction.

On the basis of the self-assessment survey, these students considered, from an emotional point of view (Table 5), that this methodology is positive and generates high degrees of engagement, excitement, interest, relaxation and focus, as well as low levels of stress. Possibly some of the values assigned by them to these emotions have some deviation due to the misunderstanding of the exact definition of this emotion as the focus and relaxation values shown should have probably been lower. In any case, the opinion of students denotes that the methodology of using chemical demonstrations in the classroom is very positive for their learning [27,28]. As stated by Liu & Huang [28] *"The more positive emotions that are induced, the more interested and focused is the chemistry learning that occurs"*. This fact has also been reflected in neuroqualitative interviews. Here, the students have agreed that they like the methodology of chemical demonstrations, because it allows them to absorb through their eyes what they have studied in class and helps them keep their attention. In this sense, Crouch *et al*. [19] has highlighted those activities which require the active participation of the students achieve better assimilation of the concepts worked in the classroom. They justify that some modifications are necessary at the procedural level so that numerical problems should be studied with greater detail through classroom demonstrations. Also, they think that chemical demonstrations should not become the only methodology as they recognize that prior and subsequent work would be necessary for classroom demonstrations to be effective.

Electrodermal activity

Electrodermal activity (Figure 3) allows for a very interesting analysis of the methodology of chemical demonstrations in chemistry learning. First, data suggests that this teaching methodology achieves a high involvement of students in the lesson. The abundance of EDA signals during the lesson (Figure 3) is possibly due to the increase in cognitive stress associated with these activities, which promotes an increase in both the tonic and phasic components of the EDA. Previous studies [33] have shown that activities that require an active participation of the student such as laboratory practices, engaging in study activities or an exam show increases in EDA signals. While the mere reception of information by the student in a passive attitude does not produce enough stimulation of the sympathetic nervous system to produce the corresponding emotional sweating response thus decreasing the electrical resistance of the skin.

The measures of the EDA of the class with demonstrations have suggested the high degree of emotional and cognitive involvement of this methodology. In fact, very high values of relative conductance are measured, produced immediately after the stimulus generated by the observed chemical process. The electrodermal response is also a useful indicator of attention and motivation, and it is widely recognized that stimuli that trigger attention and tasks that require attention cause an increase in EDA responses [31]. This, in combination with eye-tracking, suggests that this methodology helps to maintain attention during the instruction. We believe this is because chemical demonstrations are a very eye-catching and attractive teaching methodology.

Eye-tracking

We thought it would be good to be able to correlate EDA signals with what they are perceiving through the sense of sight, which can be useful to interpret the results. The eye-mind hypothesis [42] proposes that there is a correlation between what a person is looking at and what they are thinking. Based on this eye-mind hypothesis, Anderson, Bothell & Douglass [43] hypothesized that eye movement could be studied to understand cognition. The number and duration of fixation within a region can be considered as an indicator of perceived importance accompanied by a high probability of long-term memory coding [35], which, together with the electrodermal activity responses reflect the importance that certain events in the class acquire for the student. It is well known that when an individual looks at an area, that area is relevant, surprising, interesting or important [35]. It has also been determined that fixation counts are related to the number of components that the individual had to process [28]. Therefore, duration or fixation counts may actually be a suitable indicator of the student's focus areas (Table 6) [44]. The greatest fixation time value and fixations per second was generated by D-1. In addition, a very low number of revisions was presented. We assume that this means a high level of attention time to many items at the same time. On the other hand, it must be considered that it was the shortest of all, but it produced an important attraction of attention that is also manifested in the EDA responses (Figure 3).

Besides, D-2 did not produce so much eye-catching attraction (Table 6 & Figure 3b). This could be due to its own nature. Once the components (eggshell and hydrochloric acid) are mixed, the reaction process is slow, which does not make it so striking throughout the time of its performance and the teacher's explanation. D-3 (Table 6) (Figure 3c) also registered low eye-catching due to the different duration of the demonstration and explanation. Therefore, this does not mean that this demonstration lacked interest for students because, as EDA responses show, (Figure 2), this demonstration concentrated a large number of psychophysiological signals corresponding to the student's involvement at this stage of the instruction. D-4 (Table 6 & Figure 3d) shows its effectiveness with high values of fixations per second and few reviews, which implies high student's attention to this process of precipitation of lead iodide. This demonstration, despite being the second longest, was static and very colourful, with a very fast colour change, all of which attracts the attention of the students and generates strong EDA responses (Figure 2).

Eye-tracking analysis (Table 6 & Figure 3) shows that the Area of Interest defined on the teacher collects the highest values during the instruction. However, on the basis of the EDA recordings (Figure 2), the greatest number and intensity of signals are due to the demonstrations themselves (Table 6 & Figure 3b-3d). This may be an indicator that the emotions generated by them are short but very intense, assuming relevant information that memory should store. In fact, D-4 has shown very positive results in terms of attention by students. The demonstrations seem to contribute to maintain attention and improve cognitive activity without downplaying the role of the teacher guiding the lesson (Table 6). As concerns the rest of the demonstrations used in this study, a clear emotional preference by the students towards this demonstration was found thanks to these psychophysiological measure tools. These results, together with the students' responses to the survey, reveal that the precipitation reaction of lead iodide is a very good example to describe the concepts of chemical reactivity in the classroom.

As for cognitive processes, events and stimuli that are strongly emotional in content or context are better remembered than non-emotional material [28]. The emotional improvement of memory is mediated by sympathetic activation through the effects of stress hormones on the amygdala. The amygdala, in turn, is thought to modulate the consolidation of memory within the hippocampus. Therefore, the amygdala can contribute to the generation of EDA responses to outgoing stimuli that have acquired an emotional meaning through experiential learning or conditioning [31]. As based on the data extracted from our study regarding the EEG parameters and survey, number and intensity of EDA responses and also the eye-tracking analysis, it could be said that the lessons with chemical demonstrations, if well executed, contribute to excellent assimilation and long-term memory consolidation of the knowledge worked on them. In addition, it should be noted that the teacher collects the highest number of fixations, fixations per second, and reviews during the entire instruction. When supported by the EDA responses in the moments that the teacher interacts with the students, it allows us to interpret that the teacher does not lose his guiding role in the activity. Therefore, the classroom demonstrations maintain their role as supporting material for the lesson without stealing the teacher's leadership.

Questionnaires about the use of chemical demonstrations

In student learning, not only is formal knowledge of the subjects under study important, but also the affective component of knowledge [41]. When students do not perceive the validity of the learning tasks, they use superficial learning strategies (such as memorization) to learn them. In this way, the teaching strategies of the teachers and the content of sciences such as the concrete, relevant and perceptual concepts of science presented in the class stimulate the students' motivation towards learning sciences. Within the motivation in learning, other authors have established as an important factor what they call stimulation by the learning environment [41].

The results found in the questionnaires passed to the students show that they valued very favourably the use of the methodology of chemical demonstrations from the emotional point of view. The students believe that it is useful to go deeper into the course topics and consider that its use should be extended. They have also let us know that the demonstration of the precipitation of lead iodide is an excellent example to explain the concepts of chemical reactivity since it is very visual and surprising and allows them to observe an instantaneous qualitative change in the reaction medium. In the open-answer questions, all students have agreed that they like the methodology of classroom demonstrations, because it allows them to visualize what they have studied in class and helps them keep their attention. They justify that some modifications are necessary at the procedural level so that problems can be fully understood with a little more time and with classroom demonstrations. They also remark that demonstrations should not become the only methodology since they are perfectly aware that prior and subsequent work would be necessary for classroom demonstrations to be effective.

Semi-structured interview with teachers

As for the opinion of the teaching staff towards demonstrations in the classroom in general, they contemplate this methodology as something very positive and with enormous potential. Teachers say that well-executed classroom demonstrations attract the students' interest and that their regular use would help them achieve greater depth in the concepts to be studied and better assimilation of contents by students, which would definitely contribute to a more than likely improvement of academic results as far as it gets students to get involved into lesson's learning path. However, an evident shortage of hours for the adequate implementation of this methodology is widely acknowledged since not only does it require the dedication of full teaching sessions for its staging, but also a whole series of preparation tasks which have to be carefully tuned up by the teacher. Additionally, very often the low dissemination, training and information about them has played down its effectiveness. Also, in some cases, the insecurity towards this methodology makes it to be seen as unfeasible. The teachers propose that more funding be granted to the science laboratory in order to implement an applied science teaching area. Alternatively, the presence of a subject with a person in charge of this type of teaching should be necessary, someone responsible for everything related to experimentation, laboratory maintenance, inventory, classroom demonstrations, laboratory practices and so on.

Teachers consider themselves *"very immobilistic"* and assure that *"even changing student textbooks can be hard"*. That is why they demand the promotion and easy access of well-founded and previously tested material by qualified staff from the publishers covering their need for information so that all the necessary material is available and thus be able to feel more confident when introducing the chemical demonstrations in their subjects. We have seen that there are very suitable texts for the development and explanation of demonstrations in the classroom such as those by Shakhashiri BZ [22], Ford & Humphreys [45-47], among others, but in Spain they have not become too popular except for small groups of people.

The teachers also point out that the publishers supplying the school textbooks do not offer such types of texts that should help them in their work to establish a good relationship between the demonstrations and the teaching units of the official agenda. On the other hand, they consider that this methodology is very beneficial both for the student and for the teacher as it allows a constant feedback effect from both ends of the teaching-learning process. In fact, they declare that in order to encourage other colleagues to carry out their use, it would simply be necessary for them to see such demonstrations live, what it is about and the effect it causes on students, both as concerns knowledge acquisition and improvement of attention and motivation.

Limitations

Despite the large number and validity of the data collected in our work, we would have liked to have had validated questionnaires for our study. Given the lack of them, we have had to support our study by developing new tests upon the basis of our own experience. Recently, many studies have suggested that researchers should include the affective dimension in cooperation with the cognitive dimension of learning in their studies by using neuroscience methodologies because the data from these methodologies are widely accepted and provide highly objective evidence [28]. Despite having collected a wide spectrum of data to support our study, our sample is relatively small, due to the time and equipment limitations that we had. Even so, this study is a solid example of a pilot study on further exploring the use of tools commonly used in neuroscience, in educational research and not necessarily generating statistically significant results. We leave that task for further research that we hope will be supported on our pilot research [48-54].

In a future study, the aim could be to increase the size of the sample and improve its randomness, for example, trying different backgrounds such as public high schools and working with other age groups. It is also proposed to extend this study to a complete chemistry course and not only to a didactic unit like chemical reactivity, which would allow for evaluating more items in our future study. Finally, extensively collecting the opinions of the teachers about issues, applicability, motivation factors and constraints would be necessary. Evaluating the results obtained before and after a course of these characteristics in comparison with a control group doing a course based on standard learning methodology may open up new research lines [55-60].

Conclusion

This study has provided a large amount of objective data in favor of the use of chemical demonstrations in chemistry teaching of the concepts of stoichiometry and chemical reactivity. For this purpose, neurosciences tools have been used in order to evaluate the students' attention and affective parameters in a class based on chemical demonstrations at an experiential and emotional levels. Measurement of electrodermal activity, eye-tracking and electroencephalography and a neuroqualitative interview has been attempted. This study has verified that chemical demonstrations in the classroom have the potential for better cognitive assimilation of the abstract concepts of chemistry.

Moreover, this study supports the use of neuroscience tools to further study the affective sensations along with the cognitive dimension of the students' learning processes. These could also help design new activities using the aspects that most attract the student's attention to specific topics. Also, we have found very interesting factors in the difficulty of assimilating the concepts of chemical reactivity by students. First, we have reaffirmed previous studies regarding the most common difficulties and misunderstandings such as the fact that students do not admit that, before doing any stoichiometric calculation, the chemical reaction must be balanced, equal masses of reactants will react completely in a chemical equation, chemical reactants react according to the mass ratios found in a chemical equation and equal moles of reactants will react completely in a chemical reaction. The reaction products are obtained on the basis of the molar relationship with any of the reactants or the sum of them, regardless of the limiting reagent. To a large extent, after detecting and verifying these errors, many of them seem to have been partially corrected in our population after the class with demonstrations. We think that the well-executed, more widespread use of this methodology could solve many of these misunderstandings from earlier stages of learning.

Here, we have reported an interesting finding: students at this level assume that the amount of reactant that has not participated in the chemical reaction should disappear from the system and should not be included in a general equation. For this reason, we propose that demonstrations be used to show the students the role of the excess reagent in a chemical reaction. Furthermore, the potential of chemical demonstrations to reinforce new concepts of chemistry has been shown. Chemical demonstrations increase the students' affectivity towards the concepts worked on, improve their attention and enhance the effectiveness in acquiring new knowledge in the long term. In this sense, the results have shown that short and colorful demonstrations, like the lead iodide precipitation are more effective in terms of sensations than long paced ones. Besides, even with the use of demonstrations, the teacher does not lose the leading role during the instruction, which could deny the claim that chemical demonstrations are a mere distraction and reaffirm the fact that they can be an excellent support to the chemistry lesson. Finally, the interview with high school teachers has provided us with great truths about this question. 'Why are classroom demonstrations not used more regularly?' Teachers have insisted that the time factor is a clear limiter of their activity, which hinders them in their use of these types of activities. However, there are other concerns that invade them such as the safety of these experiments, the availability of resources or their ability to develop these types of sessions. They consider that it would be helpful to have more time to be able to include these methodologies in their teaching schedule, to have the help of at least one person whose function is limited exclusively to laboratories and, very important, to have suitable reliable material and easily available in Spanish which should make it possible to choose the most appropriate demonstrations and how to proceed with them throughout the instruction of a specific teaching unit such as chemical reactivity.

All these tests together confer great weight to the use of classroom demonstrations in the debate of whether or not they really are beneficial at some point in chemistry learning. Moreover, they support the use of neuroscientific tools in educational research for a significant improvement of teaching methods.

Acknowledgement

The authors thank MaCom research group (UPV) for assistance with the neuroscience technology used in this study, to the Cumbres School Valencia private school, for allowing us to carry out our study in their classrooms and M.V. Zurita-Lozano and Joan Ripoll for their valuable contribution to this work.

References

1. Huddle P, Pillay A (1996) An in-depth study of misconceptions in stoichiometry and chemical equilibrium at a South African university. J Res Sci Teach 33(1): 65-77.
2. Furio C, Azcona R, Guisasola J (2002) The learning and teaching of the concepts 'amount of substance' and 'mole': A review of the literature. Chem Educ Res Pract 3(3): 277-292.
3. Gabel D, Sherwood R (1984) Analyzing difficulties with mole-concept tasks by using familiar analog tasks. J Res Sci Teach 21(8): 843-851.
4. Schmidt HJ (1994) Stoichiometric problem solving in high school chemistry. Int J Sci Educ 16(2): 191-200.
5. Cotes S, Cotua J (2014) Using Audience Response Systems during Interactive Lectures to Promote Active Learning and Conceptual Understanding of Stoichiometry. J Chem Educ 91(5): 673-677.
6. Dahsah C, Coll RK (2008) Thai grade 10 and 11 students' understanding of stoichiometry and related concepts. Int J Sci Math Educ 6: 573-600.
7. BouJaoude S, Barakat H (2000) Secondary school students difficulties with stoichiometry. Sch Sci Rev 81(296): 91-98.
8. Sokoloff DR, Thornton RK (1997) Using Interactive Lecture Demonstrations to Create an Active Learning Environment. Phys Teach 35(6): 340-348.
9. Staver J, Lumpe A (1993) A content analysis of the presentation of the mole concept in chemistry textbooks. J Res Sci Teach 30(4): 321-337.
10. Price DS, Brooks DW (2012) Extensiveness and perceptions of lecture demonstrations in the high school chemistry classroom. Chem Educ Res Pract 13(4): 420-427.
11. Clermont CP, Borko H, Krajcik JS (1994) Comparative Study of the Pedagogical Content Knowledge of Experienced and Novice Chemical Demonstrators. J Res Sci Teach 31(4): 419-441.
12. Beasley W (1982) Teacher demonstrations: The effect on student task involvement. J Chem Educ 59(9): 789-790.
13. Shmaefsky BR (2005) MOS: The Critical Elements of Doing Effective Classroom Demonstrations. J Coll Sci Teach 35(3): 44-45.
14. Ramette RW (1980) Exothermic Reactions. J Chem Educ 57(1): 68-69.
15. Roadruck MD (1993) Chemical Demonstrations: Learning Theories Suggest Caution. J Chem Educ 70(12): 1025-1028.
16. Meyer LS, Schmidt S, Nozawa F, Panee D, Kisler M (2003) Using Demonstrations to Promote Student Comprehension in Chemistry. J Chem Educ 80(4): 431-435.
17. Tai RH, Sadler PM, Loehr JF (2005) Factors Influencing Success in Introductory College Chemistry. J Res Sci Teach 42(9): 987-1012.
18. Tai RH, Sadler PM (2007) High School Chemistry Instructional Practices and Their Association with College Chemistry Grades. J Chem Educ 84(6): 1040-1046.
19. Crouch C, Fagen A, Callan JP, Mazur E (2004) Classroom Demonstrations: Learning Tools or Entertainment? Am J Phys 72(6): 835-838.
20. Buncick MC, Betts PG, Horgan DD (2001) Using Demonstrations as a Contextual Road Map: Enhancing Course Continuity and Promoting Active Engagement in Introductory College Physics. Int J Sci Math Educ 23(12): 1237-1255.
21. Pierce DT, Pierce TW (2007) Effective Use of Demonstration Assessments in the Classroom Relative to Laboratory Topics. J Chem Educ 84(7): 1150-1155.
22. Shakhashiri BZ (1983, 1985, 1989, 1992, 2011) Chemical Demonstrations: a Handbook for Teachers of Chemistry. Madison, WI: University of Wisconsin

Press. pp. 1-5.

23. Beall H (1996) Report on the WPI Conference "Demonstrations as a Teaching Tool in Chemistry: Pro and Con. J Chem Educ 73(7): 641-642.
24. Walton PH (2002) On the use of chemical demonstrations in lectures. Univ Chem Educ 6(1): 22-27.
25. Shakhashiri BZ (1986) Exhortations for Good Teaching. J Chem Educ 63(9): 777-780.
26. Ucko DA, Schreiner R, Shakhashiri BZ (1986) An Exhibition on Everyday Chemistry, Communicating Chemistry to the Public. J Chem Educ 63(12): 1081-1086.
27. Rahayu S (2015) Evaluating the Affective Dimension in Chemistry Education. In: Kahveci M, Orgill M, Affective Dimensions in Chemistry Education. New York: Springer, pp. 29-49.
28. Liu CJ, Huang CF (2015) Neuroscience Engagement: The Influences of Chemistry Education on Affective Dimensions. In: Kahveci M, Orgill M. Affective Dimensions in Chemistry Education. New York: Springer pp. 235-258.
29. Sethi C, Dabas H, Dua C, Dalawat M, Sethia D (2018) EEG-Based Attention Feedback to Improve Focus in E-Learning. Proceedings of the 2018 2nd International Conference on Computer Science and Artificial Intelligence. Shenzhen, China: ACM New York, NY, USA, pp. 321-326.
30. Cortes KL, Kammerdiener K, Randolph A (2018) Using Multiple Psychophysiological Techniques to Triangulate the Results of Eye-Tracking Data. In: Vanden PR, Hansen SJR, Cullipher S (Eds). Eye Tracking for the Chemistry Education Researcher. American Chemical Society. Washington DC, pp. 119-143.
31. Critchley HD (2002) Electrodermal Responses: What Happens in the Brain. Neuroscientist 8(2): 132-142.
32. Dawson ME, Schell AM, Filion DL (2001) The Electrodermal System. In: Cacioppo JT, Tassinary LG, Bernston GB (Eds.), Handbook of Psychophysiology (2nd Ed.), Cambridge Press, Cambridge, pp. 200-223.
33. Poh MZ, Swenson NC, Picard RW (2010) A Wearable Sensor for Unobtrusive, Long-Term Assessment of Electrodermal Activity. IEEE Trans Biomed Eng 57(5): 1243-1252.
34. Yen MH, Yang FY (2015) Methodology and Application of Eye-Tracking Techniques in Science Education. In: Chiu MH (Ed.). Science Education Research and Practices in Taiwan. Springer. Singapore, pp. 249-277.
35. Liu CJ, Shen MH (2011) The Influence of Different Representations on Solving Concentration Problems at Elementary School. J Sci Educ Tech 20(5): 621-629.
36. Nurrenbern SC, Pickering M (1987) Concept Learning versus Problem Solving: Is There a Difference? J Chem Educ 64(6): 508-510.
37. Sawrey BA (1990) Concept Learning versus Problem Solving: Revisited. J Chem Educ 67(3): 253-254.
38. Wood C, Breyfogle B (2006) Interactive Demonstrations for Mole Ratios and Limiting Reagents. J Chem Educ 83(5): 741-748.
39. Chandrasegaran AL, Treagust DF, Waldrip BG, Chandrasegaran A (2009) Students' dilemmas in reaction stoichiometry problem solving: deducing the limiting reagent in chemical reactions. Chem Educ Res Pract 10: 14-23.
40. Inventado PS, Legaspi R, Bui TD, Suarez M (2010) Predicting Student's Appraisal of Feedback in an ITS Using Previous Affective States and Continuous Affect Labels from EEG Data. In: Wong SL, *et al*. (Eds.). Proceedings of the 18th International Conference on Computers in Education. Putrajaya, Malaysia: Asia-Pacific Society for Computers in Education. (ICCE2010).
41. Tuan HL, Chin CC, Shieh SH (2005) The development of a questionnaire to measure students' motivation towards science learning. Int J Sci Educ 27(6): 639-654.
42. Just M, Carpenter P (1984) Using eye fixations to study reading comprehension. In: Kieras D, Just M, New methods in reading comprehension research. Hillsdale, NJ: Erlbaum, pp. 152-182.
43. Anderson J, Bothell D, Douglass S (2004) Eye movements do not reflect retrieval processes: limits of the eye-mind hypothesis. Psychol Sci 15(4): 225-231.
44. Stieff M, Hegarty M, Deslongchamps G (2011) Identifying Representational Competence with Multi-Representational Displays. Cognition and Instruction 29(1): 123-145.
45. Ford LA (1993) Chemical magic. Mineola, NY: Dover Publications, Inc.
46. Alyea HND, Dutton FB (1965) Tested demonstrations in chemistry. Division of Chemical Education of the American Chemical Society.
47. Humphreys DA (1983) Demonstrating chemistry. Hamilton, Ontario: McMaster University.
48. Armario A (2006) The hypothalamic-pituitary-adrenal axis: what can it tell us about stressors? CNS Neurol Disord Drug Targets 5(5): 485-501.
49. Block N (2007) Consciousness, accessibility, and the mesh between psychology and neuroscience. Behav Brain Sci 30(5-6): 481-499.
50. Day MA, Eyer JC, Thorn BE (2014) Therapeutic Relaxation. In: Hofmann SG, Dozois DJA, The Wiley Handbook of Cognitive Behavioral Therapy, First Edition. John Wiley and Sons, New York. pp. 157-180
51. Hidi S (2006) Interest: A unique motivational variable. Educ Res Rev 1(2): 69-82.
52. https://atlasti.com/storage/whats-new-v-7-5/
53. https://es.mathworks.com/products/new_products/release2019a.html
54. https://pupil-labs.com/
55. https://www.emotiv.com/epoc/

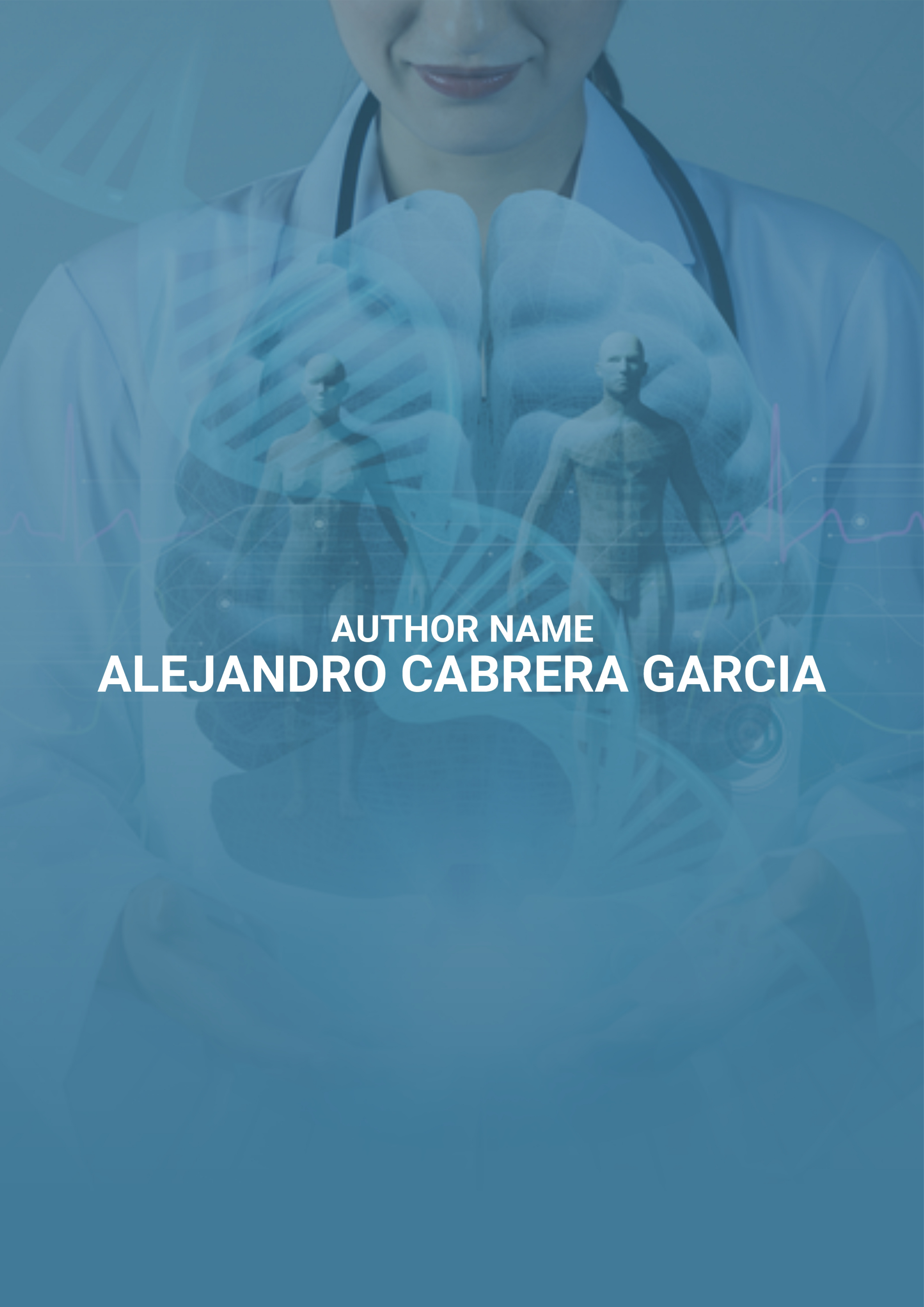
56. https://www.mindfield.de/en/

57. Kleinginna Jr PR, Kleinginna AM (1981) A Categorized List of Emotion Definitions, with Suggestions for a Consensual Definition. Motiv. Emot 5(4): 345-379.

58. Roy Y, Banville H, Albuquerque I, Gramfort A, Falk TH, *et al.* (2019) Deep learning-based electroencephalography analysis: a systematic review. J Neural Eng 16(5): 051001.

59. Steele A, Jacobs D, Siefert C, Rule R, Levine B, *et al.* (2013) Leveraging Synergy and Emotion in a Multi-Platform World. J Advert Res 53(4): 417-430.

60. Taylor GS, Schmidt C (2012) Empirical Evaluation of the Emotiv EPOC BCI Headset for the Detection of Mental Actions. Proceedings of the human factors and ergonomics society 56th annual meeting 56(1): 193-197.



AUTHOR NAME

ALEJANDRO CABRERA GARCIA