# Computer simulations for the teaching of photoelectric effect

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**Abstract.** The photoelectric effect in the production and transformation of light is an important phenomenon in quantum physics. The theory was initially presented by Albert Einstein and allows us to explain several technological applications in engineering. The use of computer simulations in the process, as they have already been proven to yield in science teaching, can provide excellent conceptual learning results, and that includes the teaching of the photoelectric effect. Ten simulations available on the internet were classified by criteria established based on bibliographic research developed within the framework of the historicity, concept, and context triad, and then four were selected and used in a classroom with engineering undergraduate sophomores. The Predict-Observe-Explain (P.O.E.) methodology was used to guide students in carrying out the experiments. The results of the analysis of the simulations and the elaboration of a laboratory instruction guide and experimental intervention, with the methodology, demonstrated the effectiveness of using computer simulations for the learning of scientific concepts in the context of engineering education.
**Keywords:** Photoelectric effect; Computer simulations; Quantum Physics; Energy; Quantum of light.

# Simulações computacionais para Ensino de Efeito Fotoelétrico

**Resumo.** O efeito fotoelétrico na produção e transformação da luz é um fenômeno importante na física quântica. A teoria foi inicialmente apresentada por Albert Einstein e nos permite explicar várias aplicações tecnológicas na engenharia. A utilização de simulações computacionais no processo, por já ter seus resultados comprovados no ensino de ciências, pode proporcionar excelentes resultados de aprendizagem conceitual, e isso inclui o ensino do efeito fotoelétrico. Dez simulações disponíveis na internet foram classificadas por critérios estabelecidos com base em pesquisa bibliográfica desenvolvida no marco da tríade historicidade, conceito e contexto e, a seguir, quatro foram selecionadas e utilizadas em uma sala de aula com alunos do segundo ano de graduação em engenharia. A metodologia Predizer-Observar-Explicar (P.O.E.) foi usada para orientar os alunos na realização dos experimentos. Os resultados da análise das simulações e da elaboração de um guia de instrução laboratorial e intervenção experimental, com a metodologia, demonstraram a eficácia da utilização de simulações computacionais para a aprendizagem de conceitos científicos no contexto do ensino de engenharia.
**Palavras-chave**: Efeito fotoelétrico; Simulações computacionais; Física quântica, Energia, Quântica de luz.

## 1. Introduction

The photoelectric effect (PE) is an important phenomenon in the teaching of quantum physics, as shown by the analysis of university physics textbooks (2010). For engineers, the photoelectric effect allows exploring technological applications such as the operation of lamps, photoelectric sensors, lasers, diodes (Jia, Ma, & Hunter, 2007) and a variety of applications and processes associated with the emission and transformation of


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light. Because of this, there is a growing interest in introducing quantum mechanics at the pre-university level and for non-physics students (especially engineers) at the university level (Sergej Faletic, 2020).

Conceptually, the phenomenon explanation is based on the "quantum of light" or "photons" (Klassen, 2011), and initially presented in the article "On a heuristic point of view about the creation and conversion of light" (Einstein, 1905). In 2015 (110 years later) Einstein's theory was widely disseminated in the International Year of Light (IYL). The recognition of the celebration of IYL by the scientific community recognizes the importance of light for the lives of human beings and justifies the realization of a bibliographic review to raise the state of the art on historicity, concept and context, with a focus on the production and transformation of light (Reis, 2019a). The discussion about this triad, presented in the review, made it possible to relate the history of science, the construction of concepts from the use of computer simulations and contextual applications in engineering.

This article consists of two parts; the first is the classification of photoelectric effect simulations and the second is the use of these simulations as mediation tools to determine students' mental modeling problems using projected methods, assessed by pre-test and post-test.

We opted to select simulations that were available for free on the internet and that would allow students to build the concepts of light intensity, frequency, current and work in photoelectric effect. The teaching processes of the phenomenon using simulation allows students to organize the independent variables and immediately observe the results in the simulated system, providing feedback (Sokolowski, 2013; Taşlidere, 2015). It also allows you to interact with the variables and evaluate the working function of particles in metals during the study of the phenomenon of photoelectric effect.

In this work, we used the Cognitive Mediation Networks Theory as the theoretical framework (CNMT) (Souza, da Silva, da Silva, Roazzi, & da Silva Carrilho, 2012), which has as its key fundamental aspect the use of the computer as an external mechanism for cognitive mediation. Our brains employ the use of internal mechanisms to operate an external processing tool, which makes it possible to use these tools as auxiliary information-processing devices. More importantly, those internal mechanisms also work as internal "hardware driver" that provide new cognitive functionalities (logical tools, models, techniques, and strategies), and such functionalities last longer than the duration of the interaction with the external tool, which has an important role in shaping the way we think. When those external tools are computer simulations, it is said that a hypercultural mediation has taken place. Especially in the teaching of Physics, the emergence of Hyperculture can provide new ways of thinking with cognitive gains, regardless of gender, social class, or level of education (Reis, 2019a; Souza et al., 2012).

The objectives of this article are to prove that the use of computer simulations has a positive impact on conceptual learning, based on bibliographic research and evidence in the classroom. In addition, the opportunity to disseminate the methodology used to examine computer simulations for the construction of a laboratory instruction guide (Reis, 2019b), built based on the study of the art of bibliographic research and evidence in the classroom. This methodology allows the classification and use of simulations to be applied in various technological tools, contributing to the effective use of digital technologies in the science teaching process.

## 2. Bibliographic research for uses of PE simulations.


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Especially for the photoelectric effect, computer simulations can not only allow the student to develop a better conceptual understanding, but they also have the advantage of enabling students to explore the phenomenon by observing relevant concepts, such as frequency, light intensity and work function of metals. Therefore, in this research, simulations were used to help students learn concepts and to relate variables in photoelectric effect phenomena.

The first record of research on the use of computer simulations with a photoelectric effect in the teaching process occurred in the United States, at the University of Washington, in the city of Seattle, Washington (Steinberg, Oberem, & McDermott, 1996). This study showed that many students at the time did not understand the experimental model well about the photoelectric effect. The study showed that many students at the time had a flawed understanding of the experimental model about the photoelectric effect. The authors pointed out that students often had the following opinions (Steinberg et al., 1996; Wittmann, Steinberg, & Redish, 2002): (i) believing that only voltage ($V = Ri$) interfered with the photoelectric effect; (ii) difficulty in differentiating light intensity (photon flow) from light frequency (photon energy); (iii) believing that the photon is charged; (iv) inability to make a current-voltage characteristic graph from an experiment involving a photoelectric effect and (v) inability to give any information about photons in the photoelectric effect. This research was essential for the development of computer simulations at the University of Colorado, through the Physics Education Technology (PhET) project.

In Brazil (PUC-MG), the use of the computer simulation of the PhET project was used together with a sequence of activities built to create Ausubel's meaningful learning (Cardoso & Dickman, 2012), according to David Ausubel's theory (Ausubel, 1968). The methodology in the photoelectric effect phenomenon was after the exploration of the previous conceptual organizers, the computer simulation was applied together with an activities script and a conceptual map, focusing on conceptual organization. At the end the authors suggested evaluating the effectiveness of using computer simulations in meaningful learning of concepts.

In Texas, researchers have investigated the use of computer simulation by the PhET group to teach the photoelectric effect in high school. Initially, students were submitted to an open question, to investigate their insights regarding the function of the battery in a photoelectric circuit (Sokolowski, 2013). After using the simulations, most students responded correctly, explaining the purpose of the battery accurately. Some students were even able to explain why the battery was the source of photocurrent production.

Methodologies for science teacher training in using computer simulations were researched at Mehmet Akif Ersoy University (Taşlidere, 2015). After an experimental intervention, students answered open questions that used the 5E model (engagement, exploration, explanation, elaboration, and evaluation), and the results showed that students considered the potential provided as a preliminary condition for the current flow in the photocell circuit. The research suggests that further investigations could integrate computer simulations with the 5E cycle to evaluate the technology effectiveness of using this technology in the learning process. In a recent study, a computer experiment was also effective in promoting a conceptual change in the understanding of the photoelectric effect for physics teachers before the service (Makiyah, Utari, & Samsudin, 2019).

## 3. Methodological foundations


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## 3.1 Methodology used to evaluate the simulations

This study analyzed different computer simulations available for free on the internet and classified them using criteria established based on bibliographic research. (Reis & Serrano, 2017). Ten simulations were chosen to work with students of Civil Engineering and Environmental and Sanitary Engineering, at the University of Contestado, in Concórdia, Santa Catarina. The criteria used in the evaluation of the ten simulators were: (a) incident light model, where the representation of the light that falls on the cathode was evaluated; (b) interaction of variables, such as current, voltage, intensity and frequency of light, during the experiment; (c) visualization of the variables and visual aspect of the application; (d) presence of an attractive and readable design for obtaining data; (e) possibility of selecting cathodes in the light incidence plate (allowing the exchange of materials); (f) graphical representation of the variables (intensity, frequency, current, voltage, and work); (f) ease of use and on-demand availability.

In order to classify the simulations, each of the defined criteria was then ranked as: excellent (E) = 3; very good (VG) = 2; good (G) = 1; or does not contain (DNC) = 0. This classification methodology was previously used to evaluate instructions for laboratories, (Reis & Serrano, 2017). For the model of the light incident on the plate, the following classification was applied: (WM) for wave model; (CM) corpuscular light model; (WCM) for a mixed or hybrid model, where the student can visualize the light as wave packets (as in simulation 10); (RM) for ray model and (NR) when the incident light was not represented.

Considering the graphical representation as an example: Simulations that presented graphs of the variables intensity, frequency, current, and voltage, a score of 3 (Excellent) was assigned. When there was little graphic representation for these variables or little relationship between the variables, a score of 2 was assigned. When the simulation allows the visualization of the variables, but not graphically, for this criterion, the simulation was scored with 1. And when there was no graphical representation or relationship between the variables, the simulation was classified as DNC (0).

## 3.2 Methodology of intervention with students[1]

The research was predominantly qualitative, the first part being a document analysis type research in the classification of the simulations, and the second part was a qualitative assessment and posterior ranking of each student's answer to the pre and post-test. (Reis, 2019b). The strategy used in structuring the script was P.O.E. (Predict-Observe-Explain), created to promote conceptual change (Tao & Gunstone, 1999). In the "Predict" step, the student must express his initial beliefs about the concepts and events that will be simulated in the virtual environment; this step is aimed at evaluating the students' previous conceptions. In the "Observe" step, the student is motivated to simulate the virtual experiment, and find the correlation among the variables presented in the simulation. And in the "Explain" step the student must explain the concept by comparing what they had anticipated in the initial step with what was observed in the experiment.

The intervention to teach the photoelectric effect was carried out with two groups of students of the Undergraduate Engineering course, in the discipline of Physics III. The interventions were carried out after approval by the research ethics committee and

[1] Ethics approval: Approved by opinion CAAE process 66848617.6.0000.5349, submitted to the ethics committee for research with humans, was submitted on 09/26/2017. Obtained concentration of the students involved for research and the publication of the data collected during the interventions.


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theoretical teaching (lectures and resolution of theoretical problems). The evaluation of conceptual learning through simulations was carried out through an instruction guide, pre-test, post-test and interviews (Reis, 2019a).

The interviews were filmed so that it was possible to use verbal and non-verbal (gestural) cues for the assessment. The students answered the interview using the Report-Aloud technique developed by our research group (Trevisan, Serrano, Wolff, & Ramos, 2019). The Report Aloud conducted an interview based on questions from a data production instrument, answered by the research subject while "thinking out loud".This technique consists of combining the student's non-verbal report of mental images with his verbal reasoning when answering a question asked in a previous and a posterior test (pre or post). After transcribing the answers, the reports were submitted to content analysis, where the categories and subcategories (according to the concepts) were generated and analyzed as proposed by Bardin (Bardin, 1977).

## 4. Results and discussions

### 4.1. Results of the classification of simulations

The use of numeric criteria to rank the computer simulations made it possible to quantitatively assess the relevance of each simulation (Table 1), for the research purposes.

**Table 1. Evaluation of simulations using criteria**

| | Light model | Interaction | Visual | Design | Cathode | Graphs | Access | Sum |
|---|---|---|---|---|---|---|---|---|
| Simulation [01] | WCM | 3 | 3 | 3 | 3 | 2 | 2 | **16** |
| Simulation [02] | WM | 2 | 3 | 3 | 3 | 1 | 3 | **15** |
| Simulation [03] | NR | 2 | 1 | 2 | 2 | 0 | 1 | **8** |
| Simulation [04] | CM | 2 | 3 | 2 | 3 | 2 | 2 | **14** |
| Simulation [05] | RM | 2 | 2 | 3 | 4 | 1 | 3 | **16** |
| Simulation [06] | RM | 2 | 2 | 3 | 2 | 1 | 3 | **13** |
| Simulation [07] | WM | 2 | 2 | 3 | 1 | 1 | 1 | **10** |
| Simulation [08] | WCM | 2 | 2 | 2 | 0 | 3 | 1 | **10** |
| Simulation [09] | NR | 1 | 1 | 1 | 1 | 1 | 1 | **6** |
| Simulation [10] | WM | 3 | 3 | 3 | 3 | 3 | 2 | **17** |

This same classification methodology was defined for each criterion established in the methodology (section 3.1). In essence, for each category, the more interactive, complete and resourceful a specific simulation was, the closer it would be to a ‘3’ ranking. With the results obtained in the evaluation score, it was possible to verify that simulations 1, 2, 5 and 10 were the best scores and, therefore, selected for the initial experiment, with 30 Engineering students (pilot experiment). The instrument used to guide students in this experiment is similar to that used in the final experiment (Reis, 2019b).

The first results obtained in this pilot experiment showed that the use of 4 simulations made the experiment extensive and exhaustive to be carried out in a short period of time (4 hours, at night). Consequently, the experiment was reduced to the use of three simulations. The criterion adopted for the removal of simulation 5 of the experiment was an access problem, because the page of this application was undergoing changes in the layout, so it was removed.

Simulation 1, for example, simulated the photoelectric effect in fluids, as in gas lamps. In simulation 2, the photoelectric effect is presented on metallic plates (in solids). And, in simulation 10, the photoelectric effect is shown in a circuit, making it possible to be related to the functioning of sensors. All of these applications are important for


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Engineering. Therefore, when a science class is taught with the aid of experiments (virtual or real) that highlights phenomena and concepts with applications of the context, the student is more likely to associate these practical experiments with the scientific model, motivating learning.

## 4.2. Results of student interventions

The final experiment was also carried out during the class period, in a computer lab, with 24 students working in groups (Fig. 1). And when there was no graphical representation or relationship between the variables, the simulation was classified as DNC (Souza et al., 2012), and the Ausubel’s Theory of Meaningful Learning (Ausubel, 1968), which assesses whether said representations were in fact used to build a better understanding of the target concepts. The classification of students' responses when answering the guide, pre and post-test and the interviews shows the positive influence of computer simulation activities in the conceptual learning in the photoelectric effect, as reported below.

**Fig. 1. Simulations performed in a computer laboratory.**

In the first question of the pre- and post-tests, the students answered objectively what would happen to the energy of the emitted electrons if the intensity of the radiation were increased. Question 2 asked what would happen to the number of emitted electrons if the frequency of the radiation were increased. Question 3 objectively asked the relation between frequency, intensity and PE. Question 4 asked about Einstein, as a Nobel Prize winner in relation to the quantum theory of light. And question 6 asked what an ammeter / voltmeter would show if the intensity of the incident light was doubled on the experiment plate.

### 4.2.1 Evidence for the light intensity concept

In order to formulate the concept of the photoelectric effect, students must correlate the intensity of the light to the flow of photons. In this case, the value of the maximum kinetic energy ($K_{max}$) of the electrons (Eq. 1) does not depend on the intensity of the light incident on the target (Halliday, Resnick, & Walker, 2011). Thus, Kmax is given by:

$$K_{max} = eV_0 \qquad \text{Eq. 1}$$

Only after using the simulations did the students answer that the energy of the particles does not depend on the intensity of the light, but on the frequency. When asked about the influence of light intensity on the electron's kinetic energy, most students answered in the pre-test that the energy of particles depends on the light intensity. As an example of the influence of simulation on the learning of this concept, in the post-test the student E5 says “*Because what counts most for the energy generated is the frequency of*


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*the light and not the intensity of it*”. When asked in an interview how their knowledge has changed (pre-test) (as expressed in the post-test); E15 refers to the visualization, of the simulation explored in one of the guide's activities with a hand gesture (Fig. 2), when replying: *Because regardless if*(sic) *you are [(00:35) # FL] in case you approach the lamp or not, what will trigger the change is the material you will have, right, if you want to change your current [(00:44) ME; EP] to be bigger or smaller.*

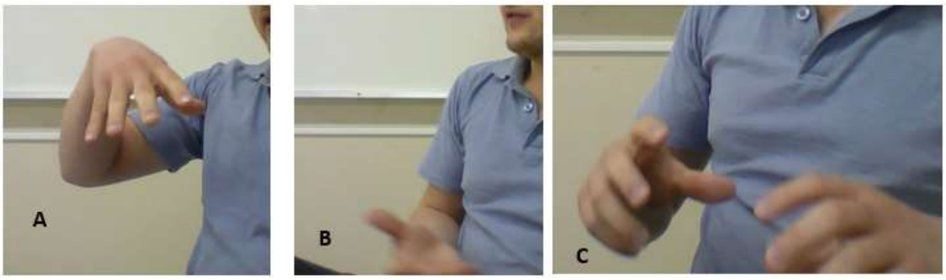


**Fig. 2. Sequence of gestures performed by the student E15 [24], showing hypercultural mediation: (A) Positions the point of light; (B) Change of material (change the plates) (C) Emission gesture (movement) of particles.**

The response of student E15, during the interview, refers to the perception for simulation 2, when using sign language indicates mental images through hypercultural mediation. Following the gestures performed by student E15, evidencing hypercultural mediation as follows: (A) Positions the point of light; (B) Change of material (change the plates) (C) Emission gesture (movement) of particles. According to CNMT, the external device used (simulations) left “internal devices” (concepts) that lasted more than the duration of the connection with the simulation. It is worth mentioning that this student missed the class in which computer activities were carried out; however, they requested access to the material and performed the activities at home.

### 4.2.2 Evidence for the concept of frequency of light

In the textbook for the concept of energy, the concept of light frequency (f) in the photoelectric effect is presented (Halliday et al., 2011). According to Einstein's theory of photoelectric effect, a quantum of light (photon) of frequency f has an energy that can be calculated with the Planck constant (Eq. 2).

$$E = hf \qquad \textit{Eq. 2}$$

When asked: "[...] if we increase the frequency, switching, for example, the red lamp by the blue one, what happens to the current generated or to the emission of electrons?", student E8 (Fig. 3) looked at the computer screen and made hand gestures while answering: *From what we saw, we analyzed the frequencies that change the most, you know, which are the ultraviolet [(01:05) # OTC] which we were able to verify a higher current than (...) for infrared. So we had an idea there even for the same material, which would generate more* (sic).


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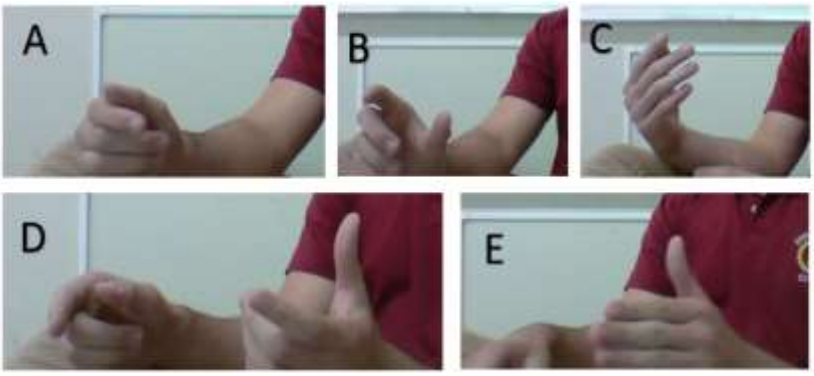


**Fig. 3. Sequence of gestures of the student E8 showing the internalization of the hypercultural mediation (Reis, 2019a). Note: (A) Infrared radiation; (B) gradually increases (C) gesture of change; (D) comparative gestures of the frequency bands; (E) establishes limit.**

In gestures, the student E8 shows a limit for light radiation at different frequencies, starting with infrared radiation (A) "up to a certain limit" (E). We believe the student was able to build conception after observing the computer simulations, which allows the user to change the frequency bands and visualize the effects in the non-visible bands (such as infrared and ultraviolet) during the simulation.

4.2.3 Design for the quantum model of light

Einstein (Einstein, 1905) proposed that light is quantized (how much light or how much energy); nowadays, this elementary quantity is called a photon (Halliday et al., 2011). According to Einstein's theory, a light quantum of frequency f has an energy that can be calculated (Eq. 2). When answering the instruments (guide and tests) (Reis, 2019b) students were asked to express their conceptions through drawing, graphically representing light in the photoelectric effect, in a way described by similar research made in Turkey (Özcan, 2015). Data analysis shows that there was a significant change in the mental image for the representation of light before (Afshar, Flores, McDonald, & Knoesel, 2007) and after the experiment (Fig. 4):

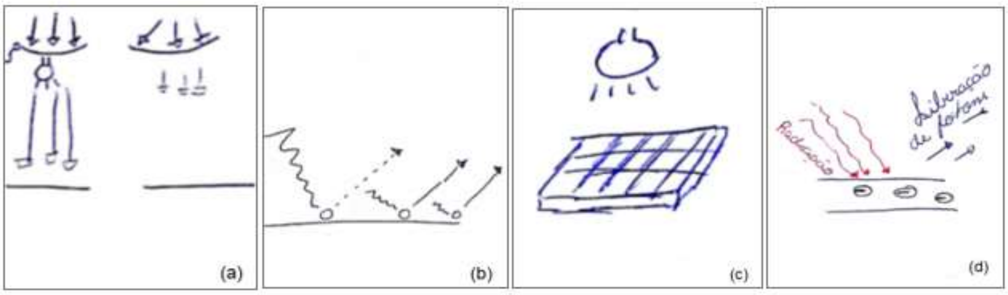


**Fig. 4 - Predominant model in the drawings presented by students (E12 and E17) when answering the pre-test (a; c) and post-test (b; d).**

Before the experiment, students represented light using its ray model, similarly to what was reported in the research carried out in Turkey. After the experiment (post-test) the hybrid model (wave-particle) predominated, similar to the light model observed in the option “show photons" in Simulation 10, which allows the visualization of light emission in photons to the material or plate (Fig. 4 b,d).

During the interview, when using a scientific model of light representation, students report their lines or gestures by hypercultural mediation, as shown in simulation


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10, relating to the microscopic nature of light (photons). Student E16, for example, refers to the perception of the change in consciousness when reporting the "photon emission" observed in the simulations. "*As we did the exercise [gesture] on the computer, I see that the light that it [...], depends on the frequency of the color ...*" (sic). Similar answers were given by students E11, E13, and E14 when referring to photons to the light model in explaining the phenomenon photoelectric effect.

Understanding the principle and theory of the photoelectric effect may lead the student to have a better understanding of science concepts in engineering. When asked about how the activities helped them in their understanding of Engineering concepts, most students answered: *"it was of great importance because it helped a lot in understanding"* (E13); or *"I found the theory/practice method interesting, made us observe the contents better, associating it with contextual applications"* (E14). Some students who participated in the research on photoelectric effect even felt motivated to write their graduation papers on the applications of the phenomenon, researching applications in the context of artificial lighting or the use of photovoltaic technologies.

**Conclusion**

The access and analysis of the simulations allowed us to conclude that there are viable simulations to be used in didactic activities, according to the teaching objectives. All selected simulations have important characteristics. The analysis carried out in this work showed that, mainly for the concepts discussed in this article, simulations 1, 2 and 10 were the ones that received the best classification in the listed criteria and were considered more suitable for the laboratory instruction guide. They allow the student to relate the simulated experiment to contextual situations in Engineering, as previously reported.

As for cognitive processes, the interventions carried out with students showed the effectiveness of this process in hypercultural external mediation. It was possible to observe that students frequently used characteristics of hypercultural external mediation when explaining concepts such as light intensity, frequency or current in a photoelectric effect. The results observed in the records show that the use of simulations with computational models can contribute to the development of a mental model for the microscopic representation of light in a photoelectric effect, according to the quantum theory of light proposed by Albert Einstein.

Finally, the study points out the importance of using computer simulations for educational purposes. The results demonstrated the importance of the effective use of digital technologies in the teaching process, enabling the expansion of this research for didactic use in online teaching activities, such as distance education. And, in this case, contribute to the individual teaching and learning process, as has been happening throughout the world during the quarantine period of the coronavirus pandemic COVID-19, as in previous research (Zunguze & Tsambe, 2021).

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SIMULATIONS LINK

Simulation [01]: https://applets.kcvs.ca/photoelectricEffect/PhotoElectric.html
Simulation [02]: https://ch301.cm.utexas.edu/simulations/photoelectric/PhotoelectricEffect.swf
Simulation [03]: https://www.wiley.com/college/halliday/0470469080/simulations/sim49/sim49.html
Simulation [04]: http://www.thephysicsaviary.com/Physics/Programs/Labs/PhotoelectricEffect/index.html
Simulation [05]: http://www.educaplus.org/luz/lcomoparticula.htm
Simulation [06]:
http://www.fisica.ufpb.br/~romero/objetosaprendizagem/Rived/20EfeitoFotoeletrico/Site/Animacao.htm
Simulation [07]: https://www.compadre.org/osp/items/detail.cfm?ID=10272
Simulation [08]:
http://iwant2study.org/lookangejss/06QuantumPhysics/ejss_model_photoelectriceffectwee1/photoelectriceffectwee1_Simulation.xhtml
Simulation [09]: https://www.walter-fendt.de/html5/phde/photoeffect_de.htm
Simulation [10]: https://phet.colorado.edu/pt_BR/simulation/legacy/photoelectric