# Investigating the Drivers and Mental Representations of the Private Interpretations of Students of Quantum Mechanics

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**ABSTRACT**

This article aims to investigate the mental images and the drivers of physics graduates, both the acquired and the modified after the use of hypercultural and social mediations. The purpose of this paper is to analyze the interpretive frameworks and the modeling present in the process of understanding fundamental concepts of Quantum Mechanics. Therefore, we adopted the harmonization of two theoretical referentials, the Cognitive Networks Mediation Theory (CNMT), because of its treatment of the hypercultural mediation, and Mario Bunge's Scientific Modeling Theory, due to his perception of the construction of knowledge in a rational way through the interpretation of reality. The results were obtained after analyzing the pre-tests, post-tests and the depictive gestures obtained from the video images recorded during the post-test interviews. Our results indicate the predominance of a 'classical realistic' interpretation in the interpretation of the students, and we also observed divergences in the propositional and analogical representations expressed during the student's explanation of the wave-particle duality as it happened in the virtual experiments.

**Keywords**: Physics Education. Quantum Mechanics. Cognitive Mediation Theory. Scientific Modeling.

## Investigando os *Drivers* e Representações Mentais Presentes nas Interpretações Privadas de Estudantes de Mecânica Quântica

**RESUMO**

Este artigo busca investigar as representações mentais e os *drivers* de licenciandos em Física, adquiridos e/ou modificados após a utilização de mediações hiperculturais e sociais. O propósito deste artigo é de constituir as correntes interpretativas e modelizações presentes no

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processo de compreensão de conceitos fundamentais da Mecânica Quântica. Para tanto, adotamos a harmonização de dois referenciais teóricos, sendo eles, a Teoria da Mediação Cognitiva (CNMT), em razão de sua abordagem relacionada à mediação hipercultural, e a Modelização Científica de Mario Bunge, em virtude de sua percepção acerca da construção de conhecimento de forma racional em meio a interpretação da realidade. Os resultados foram obtidos após as análises realizadas sob os pré-testes, pós-testes e análise dos gestos descritivos obtidos das imagens de vídeo gravadas durante as entrevistas do pós-teste. Verificamos a predominância de uma postura realista clássica nas interpretações dos alunos, também observamos divergências entre as representações proposicionais e analógicas expressadas ao longo das explicações acerca da dualidade onda-partícula presente nas bancadas virtuais.

**Palavras-chave**: Ensino de Física. Mecânica Quântica. Teoria da Mediação Cognitiva. Modelização Científica.

## INTRODUCTION

Quantum Mechanics (QM), also called Quantum Physics (QF), or Quantum Theory (QT), is considered both a solid and successful theory, since its predictions have been empirically proven, throughout this century, with accuracy. During the last decades, more specifically, it has become the foundation of technology support, used for the development of several devices, such as magnetic resonance imaging (NMR), positron emission tomography (PET), the atomic clock of the global positioning system (GPS) and, soon, used in cryptography and quantum computing (Santos, 2017).

Quantum Mechanics (MQ) researchers have a confidence of such order in its theory that the subsequent theoretical developments take it as a basic parameter in the act of thinking physics and its related phenomena (Freire, Pessoa Jr, & Bromberg, 2011). On the other hand, "[...] it is remarkable, however, that quantum mechanics has dozens of different interpretations. That is, even if there is agreement on the formalism of theory, there is no consensus on what it says in relation to reality "(Pessoa Jr, 2008, 32).

Controversies and intense debates became known because of the numerous interpretations built to clarify the results of quantum experiments. These interpretations have been developed as the theoretical advances have been consolidated, and they continue to exist. In view of these aspects, we can highlight the themes of the wave-particle duality of matter and of electromagnetic radiation. These themes provided the emergence of the multiple interpretations mentioned above, in an attempt to explain the occurrence of the observed phenomena, especially in the experimental double-slit apparatus, which, according to Feynman, Leighton and Sands (2008), is an absolutely impossible phenomena to explain classically, and contains the heart of QF itself.

Montenegro and Pessoa Jr (2002) point out that, in typical undergraduate courses, the student is expected to use quantum theory in problem solving algorithms and, when successfully developed, is approved in the discipline. However, to be successful in calculations, the student usually seeks to imagine representations of the physical world in his mind, which the authors point to representations that go beyond those observed in laboratories; the student imagines "particles like balls, imagines wave propagating, imagines a gamma-ray microscope, etc." (Montenegro & Pessoa Jr, 2002, p.1).

In this regard, we emphasize the importance of teaching QM, keeping the focus in the conceptual approach, and not only in the processes of mathematical calculations. In this way, we intend to analyze the development and use of hypercultural tools in the form of computational simulations and storyboards[1], which fill the representational gap in the behavior of the microscopic world in fundamental QM experiments, thus allowing the student to observe the representations and drivers linked to the main interpretations of the QM.

One of the great arguments of the imagistic school of mind functioning is that representations are crucial to brain processing, because they present condensed information in aiding cognition (Moreira, 2002). The absence of adequate representations at the microscopic level may thus hinder a conceptual evolution. Particularly with respect to quantum theory, which presents several possible interpretations for the same set of phenomena, it is possible that providing microscopic representations and drivers consistent with these various interpretations is important from the didactic point of view. In this way, as a research proposal in the field of Education, the study of how learning happens when the computer and digital contents are used through an external information processing mechanism is of particular interest.

Given this, the following central research question emerges:

*- Is the use of hypercultural mediation with specific microscopic representations and drivers capable of complementing the other forms of mediation and helping students to organize their thinking, following their private interpretive bias?*

Therefore, we will analyze the mental representations and drivers acquired and/or modified by physics undergraduation students after the use of hypercultural tools in the form of conceptual simulations and storyboards that provide microscopic representations of the objects and quantum phenomena. Therefore, the virtual counters and storyboards will be presented as external mechanisms of information processing throughout the process of construction of knowledge related to the Quantum Theory.

For that, we adopt as philosophical and epistemological reference the scientific models of Mario Bunge in the construction of representations of the phenomena of duality, in the material in format of storyboards, to be presented to the students. Bunge's convictions for the problem of scientific models have received increasing recognition, being employed in important analyzes and reflections in the Teaching of Sciences (Pietrocola, 1999; Cupani & Pietrocola, 2002; Westphal & Pinheiro, 2004).

[1] They are graphic organizers that can consist of a sequence of illustrations or images arranged in a previously established sequence, in order to synthesize the script visualization of an animated film, situation or situation (in our case, the behavior of the quantum object in the arrangement experimental design of the double slit). It's kind of a drawn sketch, its graphic layout may remind the reader of a comic book.

We advocate reflection on models as a segment of any study regarding the construction of knowledge in the midst of the interpretation of sensitive reality. Scientific concepts are not a copy of reality, but they are imperfect symbolic representations, capable of being perfectible, of the same. In this way, one can think that "scientific reality includes elements that may be beyond perception and must therefore be hypothetically supposed and then objectified in objects of knowledge" (Cupani & Pietrocola, 2002, p. 124).

In our educational spirit, we advocate that the study of QM should be proposed through methods that allow the student to create mental representations that help him in the phenomenological understanding of quantum concepts. In this way, we will also use as theoretical reference the Networks Cognitive Mediation Theory (CNMT), of Souza (2004), due to its approach related to hypercultural mediation, especially through the use of computers, which are technological tools responsible for performing external information, interact with internal processing mechanisms and, as a consequence, modify the individual's cognitive structure.

## THE THEORY OF COGNITIVE MEDIATION

Cognitive Networks Mediation Theory (CNMT) (Souza, 2004) is a contextualist, constructivist theory that studies the information processing of human intelligence and aims to provide a broader approach to cognition. Due to the current expansion of the digital age, CNMT seeks to explain the impacts of digital technologies on human thinking, presenting a view of cognition as an information processing phenomenon, where much of the processing is done outside the brain. It is considered an important application of CNMT its understanding of individual or collective changes, associated with the introduction of technologies as tools external to the thinking of individuals.

The elaboration and execution of a mental task on the part of the human species incorporates underlying mechanisms like storage and manipulation of data, these processes, which are taken into consideration by CNMT, occupy a "space" in human memory. In this respect, Souza (2004) cites several authors (Miller, 1956, Merkle, 1989, Ward, 1997, Lloyd, 2002, White) in suggesting that the brain and sensory organs are not powerful enough to provide the immense computational power that would be necessary to ensure the survival and well-being of the human species "(Souza, 2004, p.50).

Still regarding the capacity of human memory, CNMT considers that mental activities performed with the help of external tools would "free" memory for other activities. An example that currently affects many people, related to "memory liberation" through external tools, is that a number of years ago, several numbers of phones were stored in memory. Today, with the use of the mobile phone's agenda, which becomes an external mechanism, a smaller number of telephone numbers are stored. Therefore, the occurrence of a cognitive improvement obtained through external agents can be considered.

Given this scenario, CNMT starts with the principle that human cognition depends fundamentally on information processing, and that the isolated human brain is insufficient to explain most cognitive performance, with which it can be concluded that others information processing mechanisms are involved.

Thus, the CNMT presents the Mediation and the Extracerebral Processing of Information as mechanisms that aid in the cognitive processing. From this main idea, the author constructs a set of concepts, within his proposed theoretical framework, of which we are called the "external mechanisms of mediation" and the "internal mechanisms of mediation", seeking to bring a different perspective on what is refers to the so-called external cognition (the brain). One can cite the fact of using electronic devices – computers, tablets and smartphones – if it occurs through a process of mediation. Then, it is possible to infer that these devices become external mechanisms of mediation and that the internal mechanisms are built over time and with the need to acquire new skills for the use of these devices.

"The process by which human beings depend on external structures in order to complement the information processing done by their brains (extracerebral cognition) is called by CNMT Mediation" (Souza et al., 2012, page 2, our translation ). Figure 1 presents a synthesis of how cognitive processing occurs through environmental structures, responsible for providing an additional capacity for information processing.

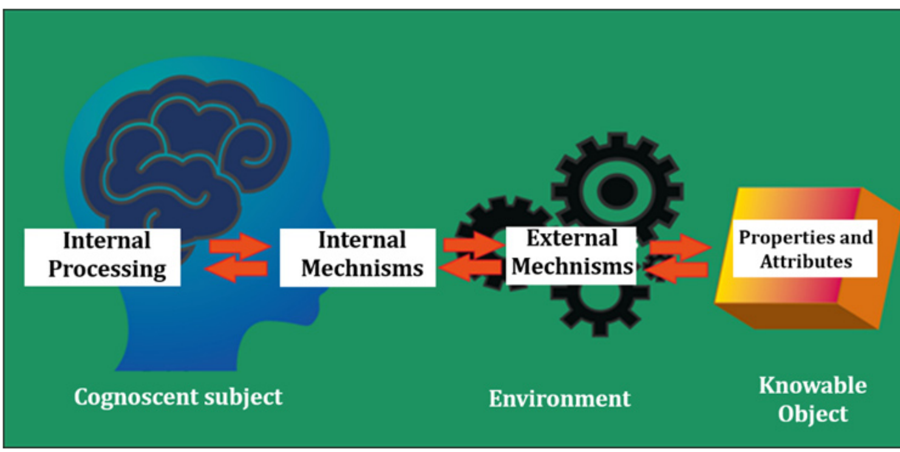


*Figure 1.* Cognitive processing through external mediation (Adapted from Souza, 2004).

In this sense, external processing is used through interaction with environment structures to increase information processing capacity. For example, when a computer is used to process information, or even perform a more complex calculation, it is using an external mediation mechanism. For this, it is necessary to construct some internal mechanisms that allow to manipulate this computer and to understand not only its processing, but also the information that it is offering.

The fundamental structure of Cognitive Mediation consists of the individual set of internal mechanisms, which makes it possible to connect external structures as auxiliary information processing devices. According to Souza (2004, p.65), “the extracerebral elements can only effectively be useful to an individual if he has a way of interacting effectively with them, according to necessity and adequately “with existing devices in the intracerebral structure that allow to translate the inputs, outputs and processing between them. In summary, it is the *drivers* that enable mediation with environmental structures.

When all these factors are taken into account, a view of human cognition arises as a sophisticated set of internal and external information processing mechanisms that together form a complex organized system.

## THE SCIENTIFIC MODELS OF MARIO BUNGE

In the sense of Bunge’s ideas, the best understanding of the world occurs as the human being moves towards the construction of theoretical knowledge. In this reason, Science presents itself as an important responsible for subsidizing the theoretical knowledge necessary for the understanding of the world in all its diversity. In this way, the reality simply observed and perceived by our senses can not be satisfactorily understood, such assimilation and appropriation of the mechanism of natural phenomena can only be achieved with the enrichment of theoretical knowledge.

According to Bunge (1974), the conceptual understanding of reality by the human being begins with idealizations and characterizations of subjects, that is, the common attributes of certain systems are verified, culminating in groupings of different classes of equivalence, thus promoting construction of a model object (or conceptual model) of a thing, fact or phenomenon.

Model-objects are described by conceptual images, symbolically representing the elements present in a real system that are sought to analyze from the perspective of a broader (or general) theory. Following this context, the model object is exposed by Bunge (1974, p.22) as “a representation of an object: now perceptible, sometimes imperceptible, always schematic and, at least in part, conventional”. Being that, the represented system can be a thing, a fact or an event/phenomenon, being able to be regarded as equivalent, even if they differ from each other.

Although reaching an auto degree of reality, the model-objects do not reach an operationalization that goes beyond gives attribution of properties and similarities of the systems. For this to happen, they must be incorporated into a body of ideas belonging to a central axis in which deductive relations can be established. Bunge (1974) points out that it is necessary to weave a formulas formula around each model object, maintaining a coherence with the body of ideas, enabling the constitution of a theoretical model (or specific theory), which is responsible for approximating/the object-model to the general theory.

Increasing the capacity for interpretation of reality, the theoretical model starts to represent the behavior of the model objects, which, in turn, describe the real objects. The theoretical model is a hypothetical-deductive system built around the object-model, produces propositions from initial assertions about the real. New situations can be interpreted, in addition to which the theoretical models were initially constructed, that is, new contour conditions can be tested, exposing the properties and behaviors of the encompassed object-models (Bunge, 1974).

According to Bunge (1974), theoretical models are submitted to empirical evidence, which can be refuted or modified by seeking interpretation and knowledge of a concrete object/situation, suggesting new ideas for changes that must be introduced to make the model more realistic. Therefore, general theories are not tested empirically, they remain unprovable.

The general theory can contemplate any aspect of reality, as long as it follows the process of theorization, in which conceptual objects are added to theories, and as product present representations of the world, in other words, provide the theoretical models that appear reality. Thus, models are built on the need to establish relationships between theories and empirical data. Pietrocola (1999) points out that in Bunge's perspective, in the scientific context, theories alone are not enough, because being abstractions made by the reason and intuition of individuals, would not apply a priori to real things. In contrast, the empirical data are closer to reality, but alone they do not have the capacity to generate knowledge. "From this apparent dichotomy between theoretical and empirical, modeling is introduced as a mediating instance" (Pietrocola, 1999, p.222).

For all these dimensions, Bunge assumes that the effective method for apprehending reality through thought is modeling, that is, the process of "converting concrete things into increasingly rich conceptual images (objects-models) and expanding them into models theoreticians progressively complex and increasingly faithful to the facts "(Bunge, 1974, p.30). Thus, Pietrocola (1999) points out that for Bunge, models are conceived as the essence of scientific work itself.

The possibility of incorporating the method of modeling in the teaching of Physics allows the conduction of activities in which students can interpret reality and represent it from general theories. Cupani and Pietrocola (2002) argue that for decades criticism has been made by students to professors, claiming that they are not useful in what is taught to them, so the authors point out that part of these criticisms could be minimized if the contents of science were presented as how to produce and validate models to explain portions of the world. "The theories seen with this modeling possibility allow us to point out ways to construct non-arbitrary representations of the world, from which explanations can be produced" (Cupani & Pietrocola, 2002, p.121).

Following the conceptual assumptions about the scientific models, we sought in our work to develop a proposal in which the students, after carrying out guided activities with software, attended a seminar in which the four main interpretations of the MQ were studied according to their explanations for the results of the double slit experiment. For this, we use as main support material the works of Pessoa Jr (1997, 2006 and 2008).

The interpretations were studied with the intention of establishing the possible theoretical models for the understanding of the results obtained in the different configurations of the experiment. This approach aimed at elucidating the students so that when asked about their interpretations for the IMZ results, they could develop mechanisms that facilitate their understanding, that is, the construction of theoretical models that can contribute to the establishment of the student in one of the interpretations of MQ.

The representations that describe the electron throughout the experimental setup idealize an element that can not be observed directly, under such a skeleton constitutes the theoretical model, producing propositions and explanations about the behavior of the model object. In summary, the theory is able to provide the explanation of a model object, producing a theoretical model of the situation in focus.

## METHODOLOGICAL DESIGN

In the activities of this proposal, the human being is taken as the main focus of the study, due to the intention to investigate the cognitive structure of the student to find out which representations and drivers are acquired and/or modified during the mediated actions. Therefore, we sought to use qualitative methods to obtain and analyze research data (Erickson, 1986). From now on, we declare that this research was submitted for analysis by the Ethics Committee on Research in Human Beings (CEP), having obtained its proper approval (CAAE: 84401317.3.0000.5349).

The research activities were developed in extra-class hours in the academic semester of 2017/2, with a sample of two students who were in the final phase of the Licentiate in Physics course. The development of the activity will be presented in five stages:

**1) Individual pre-test**: At the first moment, a pre-test was constructed and validated by the authors and later applied to the students. The test consists of nine questions, six of which are open and three are closed. The purpose of this instrument is to verify, before any hypercultural intervention (proposed by the research), students' knowledge about concepts that can lead to a private interpretation in the explanation of dual behavior of matter and electromagnetic radiation.

**2) Individual activity with two computational softwares**: In this phase, the students were given a script of activities to guide the use of the two proposed softwares. The simulators were used according to the P.O.E. (predict-observe-explain) in which students are called upon to predict the behavior of a problem situation or experiment, observe the simulation, and after these steps, explain possible differences between their conceptions and the observed (Tao & Gunstone, 1999). It is during this stage, which lasted six hours/class, that we believe that the possible internalisation of the intrinsic drives to the computational representations may occur. Mach-Zehnder's Virtual A-Interferometer software (Fig. 2-I) allows the user to observe the phenomenon of interference produced by a beam of light and by individual photons. The software B – Young's Double Slit (Fig. 2-II) allows to observe the behavior of classical and quantum objects as they pass through close and very close slits.

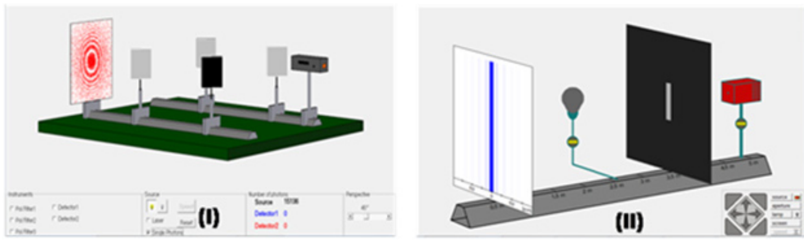


*Figure 2.* (I) Mach-Zehnder Virtual Interferometer (II) Virtual experimental arrangement of Young's Double Slit.

**3) Seminar addressing interpretations**: At this time, the students attended a seminar in which the four main interpretations of the MQ were presented according to their explanations for possible outcomes in the double-slot experimental arrangement. The material was elaborated through an adaptation of the concepts presented in Pessoa Jr.'s line of work. We sought to provide representations that idealized the behavior of the quantum object by virtue of the different interpretations recognized. Our work is based on Bunge's ideas for scientific models, in this way, we portray the model-objects, relating them to the theoretical model that predicts their behavior, all within a broader theory.

**4) Individual post-test:** A week after the end of the presentation of the interpretations, the post-test was applied to the students, containing a total of twelve questions, being open and closed, referring to the same content addressed in the pre-test, or be it the dual behavior of matter and electromagnetic radiation.

**5) Individual post-test interview**: This stage consists of individual interviews with students, based on the questions and answers of the post-test, with the main objective of providing the student's explanation for their resolutions of the questions, thus verifying which processes of thought were triggered in solving the problem presented. The interviews were conducted by an adaptation of the Think Aloud technique (Van-Someren, Barnard, & Sandberg, 1994), the Report Aloud protocol (Ramos, 2015). The difference between the methods is that in "Think Aloud" the interviewer and the interviewee maintain constant dialogue about what the interviewee is thinking about during the execution of a task, that is, while the student answers the questionnaire, he thinks aloud. Already, in Report Aloud, the student reports to the interviewer his thought process while answering the questions, that is, the student solves the questions and only then, when he finishes them, reports his thought process.

After all the interviews are done, the next step will be the analysis of the data. To do so, all the interviews were transcribed (sic) and the other instruments of data production were organized.

## ANALYSIS AND DISCUSSION OF RESULTS

The analysis is directed to the identification of the private interpretations of the undergraduate students in physics about the fundamental concepts of the MQ. In order to do this, the existing records in the instruments of data production were explored, being: questionnaires characterized as pre-test and post-test, guides for conducting activities with the software, images and video audios of the semi-structured interviews.

The verbal language, present in the transcripts of the interviews, and the written language, present in the pre, post-tests and activity guides, were analyzed based on Moraes and Galiazzi's (2007) discursive textual analysis. In turn, non-verbal language was analyzed by adapting the methodology offered by Monaghan and Clement (1999) and Stephens and Clement (2010). Characterized by means of descriptive gestures performed by the students during the interviews, the gestural analysis methodology suggests the establishment of a relation between mental representations present in the cognitive structure of the student and gestures made by the student.

Given this, we rely on the possibility of obtaining implicit student knowledge inherent in their internal visualizations (mental simulation of reasoning). Therefore, the gestures can help in the transmission of information whenever there is difficulty of verbal expression, that is, the internalized drivers can be extracted from the student. We also believe that these drivers depend directly on the types of mediations used to solve a problem situation.

In this regard, we connect the CNMT to the investigative process, linking the arguments presented by the student along the questions, with the possible external mechanisms used in previous mediating situations, with the purpose of inferring the forms of mediation that contributed most conceptually to the construction of their current interpretation of wave-particle duality. Above all, we seek to analyze the possible conceptual changes that occurred after finishing the activities composed using softwares and by the observation of macroscopic representations adapted to portray the explanations, with philosophical inclinations of each one of the four main interpretations for the double-slit results.

Next, we will present the results of two students who participated in all stages of the research. In the presentation of the results, we will not use the names of the students, they will be called "Student", followed by a number, such as "Student 1".

The first chaining of the analysis is directed to the students' view regarding the characterization and behavior of the quantum objects – photons and electrons. We can verify by means of the verbal and gestural discourse that Student 1 imagines the electron to be a sphere "*generally bluish*" (Fig. 3-I), since the photon is imagined "*like a little dot*".

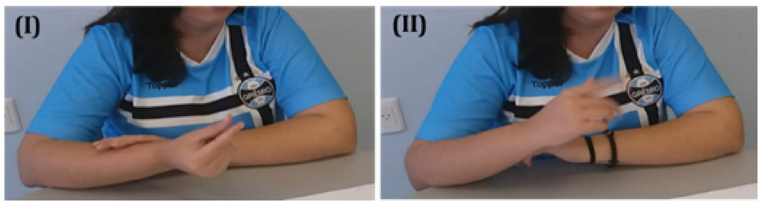


*Figure 3.* (I) thumb and forefinger simulating a small sphere. (II) Indicating finger making a sinusoidal movement.

According to the student, the representation for the electron comes from his contact with books of physics and chemistry of elementary school, characterizing, thus, a cultural mediation. The visualization of the photon is due to its interaction with computational software[2] (Fig. 4), during one of its activities carried out in the Institutional Program of Initiation to Teaching (PIBID), thus constituting a hypercultural mediation.

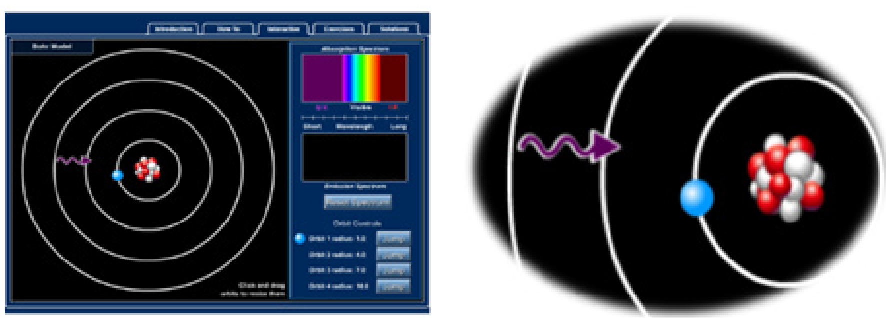

*Figure 4.* Computer simulation mentioned by Student 1.

For Student 2, the electron is also imagined to be a small sphere with an electric charge, and this representation was extracted from contact with textbooks and an interactive computational simulation[3] (Fig. 5). In this way, we can consider the occurrence of cultural and hypercultural mediation as responsible for the mental image built on the isolated electron.

[2] Available for free at https://goo.gl/XnDHTk. Accessed on: 06 June 2018.
[3] Available for free at https://goo.gl/7dXyS9. Accessed on: 06 June 2018.

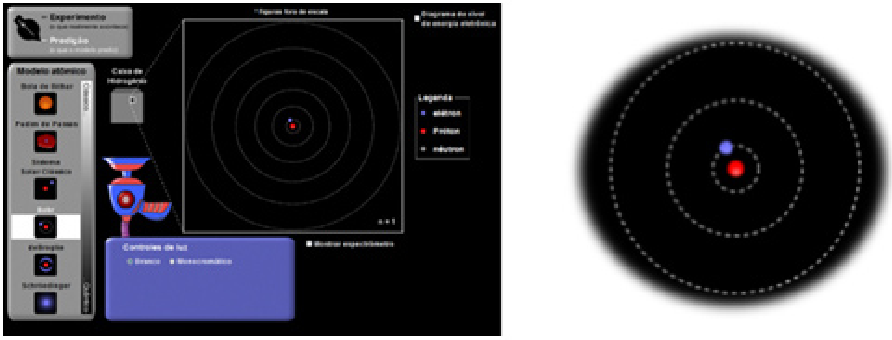

*Figure 5.* Computer simulation mentioned by Student 2.

For the photon, the student imagines an image similar to that of the electron, "*as if it were a particle*" (Fig. 6 – I), yet complements his view of the quantum object by commenting that he also thinks of the photon with an associated wave "*has an illustration that a wave appears and in this wave has one, I do not know if it is a boat, some object associated with wave* "(Fig. 6 – II) this illustration was seen by the student on the internet, in images used to explain the photoelectric effect.


*Figure 6.* (I) Representation of a spherical particle. (II) Student moving his index finger in sinusoidal movements.

In the sequence, we direct the analysis to the interpretations adopted by the students in their predictions and explanations for the results presented in the experimental arrangement of the double slit in quantum regime, with the source emitting individual electrons.

Student 1 points to an image composed of light and dark fringes, justifying his response, comments: "*It (the electron) behaves like a wave, in this question, because of the interference that it will cause*." Following the protocol report aloud, the student is motivated to expose his reasoning, so he completes:

> **Student 1**: It [electron] chooses, say, one of the slits ... And passing through the slit it has a behavior, before, even before passing through the slit it has a wave-like behavior. It passes one of the slits and as a result he ends up marking a point of constructive waves, so to speak, on the screen.

**Researcher**: [...] The electron came out of the source; do you imagine it in any format?

**Student 1**: Still with the idea of sphere with a wave behavior.

**Researcher:** Just the behavior?

**Student 1**: Only behavior.

**Researcher**: [...] Then it arrives in the double slits and what happens to it?

**Student 1**: It chooses one of them.

**Researcher**: Choose one of them, it happened ... and when does it arrive at the screen?

**Student 1**: You have the question of constructive and destructive waves, right? The behavior issue ...

Given this excerpt, we can verify that Student 1 remains with a mental image of the electron in spherical format throughout all experimental setup, but it confers an undulatory behavior in its response. We therefore accept the possibility that the student is using, in a certain sense, quantum logic, since the student correctly states the answer, but she shows difficulties in explaining the interference pattern. The driver used by the student to respond to the problem is not modified enough to establish justifications for the observed phenomenon, since she still considers the quantum object imagined as being a classic and indivisible corpuscle, throughout the course of experimentation and yet to him an undulatory behavior is expected.

Student 2, asked about the same questioning, demonstrates that there are doubts in two possible answers, one of which is represented by clear points in all regions of the bulkhead without any specific format (corpuscular pattern) and the other in which there is a formation of a characteristic interference pattern.

To justify its possible choice for the interference figure, the student is said to be inspired by the response to the experimental arrangement of the double slit with the source, emitting a beam of light, yet explains "*it [electron], although it is one at a time, would maintain its same undulatory behavior, would suffer diffraction there*." Next, however, the student, when encouraged to express his or her imagination about the behavior of the quantum object, suggests imagining a particle being emitted by the source "*as if it were a particle in the air swinging*."

Considering the disagreements in the explanations provided for the result of the experiment, we can verify that the drivers composed by corpuscular notions are resistant to change. Another point that corroborates this difficulty of adoption for an interpretive line that justifies the results obtained in the screen can be observed in the following excerpt.

**Researcher:** Then, come in front of the two slits, you think what happens?

**Student 2**: In one of them it will pass.

> **Student 2**: Yeah, or it hits and is reflected. I imagine that not everyone goes out with the same pattern ...
>
> **Researcher**: Got it.
>
> **Student 2**: Not everyone will go to the same side, anyway. So, I think that it would keep the same pattern [interference], but it would take longer to get that format. But I am not sure either, because there is a lack of interaction between the others. This leads me to imagine that non-interference is also a possible alternative.

We see that doubts arise as to the pattern formed in the shield, there are divergences between theoretical knowledge (in the form of a propositional representation) for the result about the classical configuration of the double slit, and the imagistic formulation to understand and explain the "wave results" in the quantum regime.

In this segment, the student presents doubts on the pattern to be formed in the shield, his initial hesitation in pointing out a pattern of interference as a result is apparently due to his difficulty in observing an undulatory behavior for his mental images, corpuscular, regarding the electron. In its cultural charge, the student recognizes fundamental propositions of the wave-particle duality and tries to implant in its analogical representations, however, the corpuscular image for the electron, which stands out at the moment of the construction of meanings and understanding of the phenomenon.

In view of the arguments used by Students 1 and 2, we recognize the simultaneous use of propositional and analogical mental representations, thus provoking a dissonance, a kind of tension in the dialogue and interconnection between the two. The propositional ones incline to the wave behavior, seeking to confer characteristic sentences like, "*It (the electron) behaves like wave in this question, because of the interference that it will cause*" (Student 1), to defend the pattern of interference formed in the screen. Analogs are present and approximate to the corpuscular behavior, since the student accepts the interference pattern, but still has the (classical) image of the sphere for the electron, during the whole arrangement of the double slit.

In Johnson-Laird's (1983) perspective on mental models and the ideas pointed out in the work of Dias and Meneses (1993), the mental representations of knowledge constructed by the subjects can be hybrid, that is, capable of incorporating propositions and mental images during the understanding of a phenomenon. One of the difficulties in MQ's conceptual learning, we believe, is that the student has an understanding of information of a propositional nature and can not establish an association with the analogical representations experienced throughout his or her academic and consolidated trajectory in his/her cognitive structure.

This non-establishment of relationship and dialogue between mental representations may not be consistent with an epistemological obstacle from the Bachelardian point of view, but rather, according to our perception, it is, in fact, a representational obstacle. In this regard, we consider that, in the conceptual teaching of central topics of the QM, such as wave-particle duality, mental representations are manipulated in consonance, aiming to awaken the student's consciousness, so that it uses analogical representations that dialogue with the propositional ones, facilitating the own understanding of the interpretative essence of the observed phenomena.

Continuing the presentation and analysis of the results, the students' interpretations will be evaluated for the results of the IMZ in a single-phase regime, in which the source emits a few hours, being regulated to emit only one photon at a time, that is, one second photon will only be released when the previous one has already reached the bulkhead. For this experimental configuration, Student 1 illustrated as a response a rectangular and central figure to be formed in the visualization screen, recognizing to have imagined a corpuscular behavior for the photons.

The reasoning developed to solve the problem can be better understood with the following excerpt

> **Student 1**: A photon comes out of the source, it divides (Fig. 7-I) and at the end it joins (Fig. 7-II) forming a single particle. Hence in this way it is in the center itself, not in the center, but where the beam of the mirror is positioned. In the mirror line.
>
> **Researcher**: [...] and when he leaves here you imagine him in what format, before going in the first mirror?
>
> **Student 1**: I still find him a sphere.
>
> **Researcher**: A sphere. There he goes ...
>
> **Student 1**: If dividing into smaller size (Fig. 7-III), in case it divides that size.

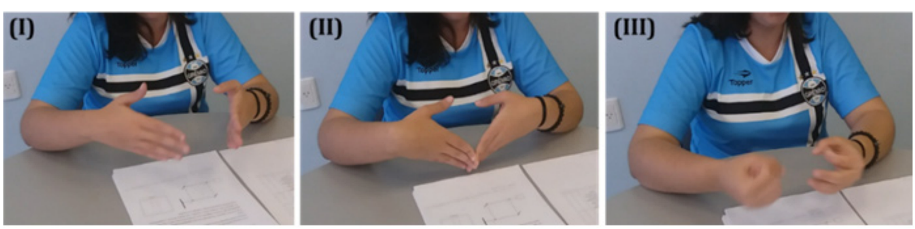


*Figure 7.* (I) Division of the photon into two parts. (II) Union of the two parts of the photon. (III) Two smaller spheres, resulting from the division of a larger sphere – the photon.

The expressed verbal and gestural language reinforces the inclinations for the adoption of the corpuscular interpretation when explaining the behavior of the photon in the experimental setup. The student does not dissociate the representation of the classic corpuscle to the quantum object. In this case, the photon is imagined by dividing into two smaller spheres, differently from the explanation used for the results of the double slit. In this way, we verified a change in the student's driver in his modeling to seek explanations of the proposed problem.

This change in the driver and the construction of the model comes, according to the student, from his interaction with the virtual stands and representations of the interpretations for the double slit, "*I thought trying to associate what we did in the two of the simulation, I tried some* (explanation) ... ". However, the pattern drawn does not match the result presented by the software. Even if he has cited hypercultural activities as auxiliaries, we can verify that the mediations performed in this case did not provide a correct understanding of the empirical result. In this case, we observe the use of analogical representations in Student 1's statement. Sign language refers directly to its mental image that is bound to the corpuscular behavior for the photon along the IMZ.

When asked about the same experimental arrangement, Student 2 chose to draw a "*diffraction pattern, with the highest incidence in the center and has clear and dark fringes expanding right up to the periphery*" (Fig. 8-I). This choice was based on its interaction with the virtual experiment (Fig. 8-II), together with the association of an image observed at the time of an experiment carried out along the graduation in which it verifies the Fresnel point (Fig. III) with the aid of a laser and a pin.

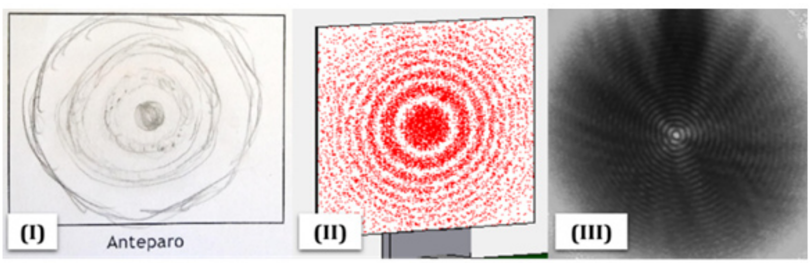


*Figure 8.* (I) Figure drawn in the post-test. (II) Standard presented in the software. (III) Image representing the Fresnel point.

When asked to explain the reason for the formation of this pattern, the student claims to imagine the corpuscle-shaped photon with an associated wave, dividing into two as it passes through the first semi-reflecting mirror, "*two smaller spheres with their associated waves at times in phase or out of phase right*." But when arriving at the second semi-reflective mirror, the student states that he does not know what are the factors responsible for the occurrence of the interference pattern, as can be seen in the following excerpt from the interview:

> **Researcher**: To form the pattern of interference, do you imagine this division?
>
> **Student 2**: Yes. Then I imagine ... I can not imagine what happened here [in the semi reflective mirror] exactly to form this pattern. This here came from the memory I had of the [IMZ] experiment.
>
> **Researcher**: And you spoke about this division, you watched it where?

> **Student 2**: I read an article in <a science dissemination magazine> that was Schrödinger's Cat, it is a Brazilian who did an experiment there, she put an image on a screen, there was divided the beam, a part of the beam passed through this screen that had the image of a cat and the other went to the reflecting mirror and went to the screen.

The mental image in which the photon divides is the result of reading about the images and description of the Schrödinger's cat experiment, the student ends up not imagining it with wave characteristics, making it difficult to determine the possible agents responsible for the appearance of light and dark fringes in the bulkhead. Since the image of the result alone is known due to the interaction with the virtual workbench, it is the consequence of a hypercultural mediation in which there is an interpretative gap about the quantum behavior. We expected the student to model the situation and, based on the interpretations, to fill this conceptual gap with certain concepts and representations that convinced him to "accept" the experimental result.

Considering the core of externalized thoughts throughout the explanations, we have identified important evidences that characterize a realistic philosophical posture adopted by Student 1 in the face of the proposed situations-problems. Interpreting the results of the double-slit quantum regime, the student uses a mental image in which the electron is considered a corpuscle in every experiment. Even if it predicts the interference pattern (mechanical response), the student resists modifying his driver, that is, ontologically the electron remains a corpuscle, even though it forms an interference pattern in the shield.

Student 1's prediction for the IMZ results reinforces the finding of classic realist thinking in its arguments. Throughout the experimental arrangement, the photon is imagined as a spherical-shaped corpuscle, which, upon finding a semi-reflecting mirror, divides into two smaller spheres. The figures drawn on the screen also illustrate a corpuscular behavior, with absence of an interference image. In view of these considerations, we can, according to Montenegro and Pessoa Jr (2002), reach an incipient Corpuscular interpretation (Realistic) manifested by Student 1, since he judges microscopic (or at least resting mass) entities as particles, without consolidated elements regarding the undulating bias.

Considering the collective of ideas expressed throughout the interpretations about the proposed phenomena with the suggested configurations for the virtual counters, we recognize important traits that also configure a realistic mindset of Student 2 about the behavior of quantum objects, such as the slopes adopted by Student 1.

For both the double-slit experiment and the IMZ, both in quantum regime, the undergraduation students adheres to corpuscular representations for photons and electrons, exposing difficulties in understanding and explaining the patterns of interference formed in specific situations of the experimental arrangements. Even though predictions for results were considered correct for the most part, conceptual understanding did not maintain the same success, given the interpretative gaps present in the student's discourse, such as the dichotomy between responses, characterizing an undulatory behavior with the presence of a pattern of interference, and explanation, beckoning to imagistic elements that construct a corpuscular image about the nature of the electron/photon. Thus, in view of the above and in accordance with the ideas of Montenegro and Pessoa Jr (2002), we conceive the interpretation Corpuscular (Realistic) as more influential conception manifested by the student, since it adopts as particles the quantum entities in their mental processes of reasoning.

## FINAL CONSIDERATIONS

In this investigation, we seek to examine the development of a theoretical-methodological design in order to understand how mediations composed by virtual stands and storyboards with specific microscopic representations and drivers can help Physics graduates to develop their reasoning, following a certain interpretive chain. Thus, during the analysis movement, we try to elucidate the influences of external processing, resulting from the mediations in the private interpretations and mental representations outsourced by the students.

Considering the obtained results, we verified that both students presented a classic realistic interpretation along their explanations for the results of the double slit and the IMZ in quantum regime. The results predicted by the students were generally considered certain and confirmed experimentally, however, their reasoning did not confirm the success of phenomenological understanding. For example, the expected interference patterns for individual electrons and photons, in the absence of detectors, were not comfortably explained because of the intrinsic corpuscular interpretation adopted by the students.

The virtual counters and the interpretations with specific representations for the results of the double slit contributed to the predictability of students' responses to each experimental configuration. However, in their explanations the cultural burdens experienced prevailed, the representations of the four main interpretations were not mentioned explicitly in the moments directed to the analysis of the double slit.

Regarding the conceptual understanding of the results obtained in the IMZ, we expected students to perform a modeling to understand and explain the experimental results. This modeling would be based on their observations about the approaches of each of the four main interpretations of the QM. That is, a transposition of the explanations of the double slit to those of the IMZ. However, the possible theoretical models directed to the conceptual understanding of the IMZ were constructed based on situations experienced along their academic trajectories, in which much reinforce the classic and realistic posture.

Analyzing the mental representations used by the two students along their answers, we perceive significant divergences between the propositional and the analogical representations. The difficulties presented throughout the explanations showed the non-agreement in the use of the mental images with the respective propositions, and, therefore, did not establish a dialogue, that is, they did not converge to the understanding of the experimental results.

We can emphasize that mental images, especially those of classical origin, stand out at the moment of interpretation and modeling, when they seek the understanding of wave-particle duality phenomena observed in virtual double-slot and IMZ. The propositional representations, most often with wave inclinations, arose in the student's discourse as the mental images available in their cognitive structure could not be modified to the point of solving the problems proposed. There are moments, especially when stimulated during the interviews, that students try to introduce elements of wave representations because of their propositional representations, yet these moments are scarce.

In the perspective of Cognitive Psychology, people do not understand the world directly, they perceive it through the very construction of mental representations. Therefore, mental representations, or also called internal representations, are ways of internally re-presenting the external world (Moreira, 1996). In light of this, we reinforce the importance of promoting research that is dedicated to the interpretive and representational current directed to the teaching and learning of topics of MQ, so that it becomes a more pertinent contribution to researchers in the area of Science Teaching.

Finally, we understand that, in physics teaching, it becomes important to develop methodologies and didactic strategies that emphasize the conceptual and interpretative instruction of quantum phenomena, especially in teacher training courses, but without neglecting the basic mathematical paths and necessary for the construction of quantum formalism. We therefore agree with a reversal of "priorities" in the teaching processes of the introductory disciplines of MQ, since, according to the literature, most courses prioritize the algorithms of resolution, leaving the wealth of phenomena in the background.

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## REFERENCES

Bunge, M. (1974). *Teoria e Realidade*: editora Perspectiva S.A., São Paulo.

Stephens, A. L., & Clement, J. J. (2010). Documenting the use of expert scientific reasoning processes by high school physics students. *Physical Review Special Topics-Physics Education Research*, *6*(2), 020122.

Cupani, A. O., & Pietrocola, M. (2002). A relevância da epistemologia de Mario Bunge para o ensino de ciências. *Caderno Brasileiro de Ensino de Física*, *19*, 100-125.

Dias, P., & Meneses, M. I. C. (1993). Problemática da representação em hipertexto. *Revista Portuguesa de Educação*, *6*(3), 83 – 92.

Erickson, F. (1986). Qualitative methods in research on teaching. In Wittrock, M.C. (Ed.). *Handbook of research on teaching*. New York: Macmillan Publishing. pp.119-161.
Feynman, R. P., Leighton, R. B., & Sands, M. (2008). *Lições de Física – The Feynman lecture on Physics* (Vol.3). Porto Alegre: Bookman.
Freire Jr, O., Pessoa Jr, O., & Bromberg, J. L. (2011). *Teoria quântica: estudos históricos e implicações culturais*. Campina Grande: EDUEPB.
Johnson-Laird, P. N. (1983). *Mental models*. Cambridge, MA: Harvard University Press.
Monaghan, J. M., & Clement, J. (1999). Use of a computer simulation to develop mental simulations for understanding relative motion concepts. *International Journal of Science Education*, *21*(9), 921-944.
Montenegro, R. L., & Pessoa Jr, O. (2002). Interpretações da teoria quântica e as concepções dos alunos do curso de física. *Investigações em ensino de ciências*, *7*(2), 107-126.
Moraes, R., & Galiazzi, M. C. (2007). *Análise Textual Discursiva*. Ijuí: Editora Unijuí.
Moreira, M. A. (2002). *Investigación em Educación em Ciencias*: Métodos Cualitativos, Texto de Apoyo nº 14, Programa Internacional de Doctorado em Enseñanza de las Ciencias, Universidad de Burgos, España.
Moreira, M. A. (1996). Modelos mentais. *Investigações em ensino de ciências.* Porto Alegre. *1*(3), 193-232.
Pessoa Jr, O. (2006). *Conceitos de física quântica*. São Paulo: Livraria da Física,v. 1.
Pessoa Jr, O. (2008). *Conceitos de física quântica*. São Paulo: Livraria da Física,v. 2.
Pessoa Jr, O. (1997). Interferometria, Interpretação e Intuição: uma Introdução Conceitual a Física Quântica. *Revista Brasileira de Ensino de Física*, *19*(1).
Pietrocola, M. (1999). Construção e Realidade: o realismo científico de Mário Bunge e o ensino de ciências através de modelos. *Investigações em Ensino de Ciências*, Porto Alegre, *4*(3).
Ramos, A. F. (2015). *Estudo do Processo de Internalização de Conceitos de Química Utilizando Software de Modelagem Molecular:* Uma proposta para o ensino médio e superior. 2015. 230 f. Tese (Doutorado – Ensino de Ciências e Matemática), Universidade Luterana do Brasil, Canoas.
Santos, A. C. (2017). The IBM Quantum Computer and the IBM Quantum Experience. *Revista Brasileira de Ensino de Física*, *39*(1).
Souza, B. C. (2004). *A Teoria da Mediação Cognitiva*: os impactos cognitivos da hipercultura e da mediação digital. 2004. 282 f. Tese (Doutorado – Curso de Psicologia), Universidade Federal de Pernambuco, Recife.
Souza, B. C., Da Silva, A. S., Da Silva, A. M., Roazzi, A., & da Silva Carrilho, S. L. (2012). Putting the Cognitive Mediation Networks Theory to the test: Evaluation of a framework for understanding the digital age. *Computers in human behavior*, *28*(6), 2320-2330.
Stephens, A. L., & Clement, J. J. (2010). Documenting the use of expert scientific reasoning process by high school physics students. *Physics Education Research*, *6*(2).
Tao, P. K., & Gunstone, R. F. (1999). A process of conceptual change in force and motion during computer-supported Physics instruction. *Journal of Research in Science Teaching*, *37*(2), 859-882.

Van-Someren, M. W., Barnard, Y. F., & Sandberg, J. A. C. (1994). *The Think Aloud Method: a practical guide to modeling cognitive processes*. Academic Press. London.

Westphal, M., & Pinheiro, T. C. (2004). A epistemologia de Mario Bunge e sua contribuição para o Ensino de Ciências. *Ciência & educação*, Bauru, 10(3), 585-596.