Peer-Reviewed Article

Volume 10, Issue 2 (2021), pp. 27-48
Journal of Interdisciplinary Studies in Education
ISSN: 2166-2681 Print 2690-0408 Online
https://ojed.org/jise

What Can Quantum Physicists Tell Educators?

Selma Dündar-Coecke
University College London, UK

ABSTRACT

The purpose of this study is to investigate physicists' views about the possible impacts of recent developments in quantum physics on educational implementations, particularly on science learning. Throughout the research a mixed-methods strategy was used. The data were collected from the physicists working at the European Organization for Nuclear Research (CERN). The qualitative and quantitative results were compared to portray the consistency between the two cohorts. The results indicated that the physicists' experiences could provide valuable contributions to educational practices, and both teachers and students could benefit from the knowledge exchange between the field specialists. The implications for, and potential contributions to educational practices are discussed, taking into account the three most pertinent subfields, namely curriculum, learning, and teaching methods.

Keywords: Education, science education, teaching, learning, quantum physics, mixed methods.

A new science movement gained momentum in the 20th century, seeking explanations to rationale of anomalies initially in physics, then chemistry, biology, and later moving into the social sciences (Gray-Donald, 2007). In the years to follow, experiments with light have been at the forefront to test of counterintuitive theories conflicting with Newton's descriptions of the nature of light. For instance, one of the early experiments 'double-slit' showed that at quantum level while particles behave like waves, waves also behave like particles. Later, this caused doubts about the traditional ways of understanding the act of human observation and the role of observer. Because in such experiments a human being decides to observe properties of quantum system at a particular time and space, and therefore, human consciousness constituting physical reality may play a role when registering the dualities. A parallel line of thought proposed that most anomalies of the quantum world need new ways of thinking (Bohr, 1958), even most Newtonian concepts should be abandoned, as most of them may be meaningless by context or constrain our thinking about reality at quantum level, particularly when new ways of thinking about phenomena are required (Heisenberg, 1955, 1958).

Later developments in physics accelerated the rise of quantum mechanics, amounting to a revolution in science, and influencing, for instance, K. Popper's inductivist views on the scientific method (see the theory of falsification; 1951, 1982, 2002). The transition from classical Newtonian physics to quantum mechanics was also represented in the Kuhnian paradigm shift (Kuhn, 1962), which portrayed the characteristics of scientific revolutions and their instruments as emerging from major distinctions between two perspectives. While the Newtonian worldview portrayed reality in an objective, determinist, and certain way (Cantley, 2015), new science encouraged researchers to redefine fundamental concepts and proposed that objectivity might be confounded by measurement style and perception.

An increasing number of educationalists have acknowledged these developments and discussed education theory in relation to the new science, with a particular interest in science teaching, curriculum, and the role of learners in the postmodern world (see e.g., Dündar, 2012; Hunter & Benson, 1997; Reigeluth, 2008). Representing this line of thought, it is argued that if reality is uncertain, then chaos and complexity are also inevitable in the present-day curriculum and classrooms. In such an environment, measurements can be corrupted by the measurement processes themselves (Mason, 2008). Learning therefore may not mean a direct transmission from teacher to student either; instead, it can occur in a non-linear manner through exploration, where necessary skills cannot be strictly quantized. In this context, the idea of the measurability of skills becomes highly relative and problematic, the nature of truth being another ambiguous topic for learners.

Others discussed the impacts of this major shift in scientific inquiry and how it is reflected in science teaching. A number of educationalists shared opinions about how physics content and instruction can be improved, or why quantum theory needs to become a part of school curriculum from the upper secondary school level and onwards (Fraser et al., 2014; Henriksen et al., 2014; Jonston et al., 1998; Krijtenburg-Lewerissa, 2017; Michelini et al., 2000; Vokos et al., 2000). A recent experiment has rendered the way how such complex theory can be taught more efficiently using graphical formalisms -a much more convenient approach for younger learners (Coecke, Gogioso, Kissinger, Pfaendler, Dündar-Coecke, Khan, in preparation). Others introduced the role of peer instruction (Mazur, 1997; Watkins & Mazur, 2013). Research also showed that although a mathematical background is necessary to build conceptual understanding, it is not alone sufficient (Koopman et al., 2008), as both procedural and conceptual knowledge is necessary for the formation of the required skills in physics (Papaphotis & Tsaparlis, 2008).

Despite these, research in the field of education is somehow sparse, possibly due to lack of interactions. Some researchers discuss that best solution would be to act upon school settings. For instance, one way of dealing with the increase in complexity of physics content could be relating reforms through the integrated curriculum, and in a narrower sense through integrated sciences. Another way is to consider changes in scientific perspectives, providing opportunities to design modules and courses in an open and flexible way through liquid curricula as opposed to a crystalized form to ensure flexibility in learning (see e.g., Chabay & Sherwood, 2015; 2014; Savin-Baden, 2008; Steils et al., 2014).

As part of a wider scale discussion, it is helpful to directly consider whether the paradigm shift in physics has foreseeable impacts on the theory of education and on educational implementations. The present study therefore postulates that analyzing the perspectives of quantum field experts may contribute to sustainable development in education. Such analysis also aims to assure bidirectional communication to improve the potential these fields carry for each other. Moreover, it becomes easier for researchers from both sides to understand whether contemporary experiments provide new insights into educational practices, in particular when the functions of education are considered.

The aim here therefore is to take a step forward and explore, from theorists' and experimentalists' perspectives, whether recent developments in quantum physics are relevant to education, particularly if these developments can have impacts on the way we teach/learn science in schools. Two studies, following different paradigms, explored this, each focusing on separate research questions.

The first study aimed to address whether the experiences of quantum physicists can be transformed into insights that can be used in the science of education. The second study focused on how realistic these insights are when the impacts of recent developments in quantum physics on educational practices are considered. It was aimed at answering, "To what extent do developments in quantum physics have an impact on educational practices?"

Responses were analysed using a mixed-methods design. The first study employed a qualitative (theory generation) approach, and the second followed the quantitative paradigm. The mixed methods approach enabled researcher to deal with the degree of complexity and advanced the rigor.

RESEARCH METHOD

The present research employed a mixed-methods sequential explanatory design, which combined two consecutive phases within one program (see Creswell, 2005; Teddlie & Tashakkori, 2009). This began with collecting and analyzing qualitative data to explore the research question of the Study 1. From that exploration, the second phase (Study 2) was organized, where quantitative data were collected and analyzed, to elaborate on whether the initial findings could be generalized over a large sample (see Creswell, 2005; Strauss, 1987; Smith & Eatough, 2006).

Study 1

The first study used a qualitative approach which, in contrast to quantitative paradigms, explores the unique features and circumstances surrounding a particular case (Ernest, 1997). This approach relies primarily on interpretation rather than measurement, where participants express their beliefs rather than facts. The qualitative approach does not necessarily require predetermined hypotheses; instead, it requires the researcher to observe, intuit and sense what is occurring in the natural environment (Morrow, 2005). The purpose of this phase therefore is to deeply understand the meaning of participants' beliefs and desires. To achieve this, complex, rich interpretations were revealed with 'why' and 'how' questions rather than 'how many'. (Litosseliti, 2003; Strauss & Corbin, 1990).

Participants

The qualitative data were obtained using a focus group interview method to provide discussion-based views and produce particular types of qualitative data through group interactions (Millward, 2006). The type of interaction for this topic is particularly important not simply because it reveals participants' views, values, or linguistic approaches, but also because it allows deep conversations that enable participants to hear each other, stimulate their thoughts, and reconsider their own understandings and experiences, rather than focusing on numbers alone (see Litosseliti, 2003; Millward, 2006).

The recommendation on group sizes for this kind of research ranges from four to eight -Morgan (1993) suggests six to twelve; Creswell (2005) idealizes it at around four to six; Litosseliti (2003) and Krueger (1994) ranges between eight to twelve. Given that the participants had an in-depth knowledge of the focal topic, a small group design was preferred. The target of this method was not to infer but to understand, not to generalize but to determine the participants' opinions (Krueger, 1994; Litosseliti, 2003; Gawlik, 2017). The sample therefore consisted of six physicists working at the European Organization for Nuclear Research (CERN), allowing the participants to discuss the topic, share their experiences, and pose more in-depth follow-up questions.

The study employed purposive sampling rather than random. The benefit of the purposive sampling is that it enabled the researcher to select a relatively small number of participants, as typically associated with a qualitative research paradigm (Teddlie & Tashakkori, 2009; Patton, 1990; Maxwell, 1997). A group of participants was invited to take part in the research with the help of the head of the Education Outreach Group at CERN, based on the three criteria as (1) willingness to participate, (2) availability, (3) the level of expertise (e.g., it was deemed important that the scientists should have held their present position for at least one year). Care was also taken to ensure that each participant worked on a different experiment at CERN. Table 1 demonstrates the sample profile.

Table 1: The demographics of the focus group participants

Code	Country	Graduation	Gender	Field	Position at CERN	Age group	Time in field
1	Germany	Germany	Male	Antimatter, particle physics	ATNENA experiment	56-60	31-35 years
2	Japan	Japan and USA	Male	High energy, particle physics	ATLAS experiment	36-40	11-15 years
3	England	England and USA	Male	Particle physics	CMS experiment	31-35	6-10 years
4	Greece	Greece	Female	Atomic energy	DMS experiment	41-45	11-15 years
5	USA	Turkey and USA	Male	Experimental high energy	Physics and Astronomy	26-30	6-10 years
6	Russia	South Africa and USA	Female	Applied physics	CMS experiment CLIC project leader	31-35	11-15 years

Materials

A semi-structured interview form was used to collect the data. The draft interview form was constructed by considering the literature and research objectives in relation to a number of possible categories. The draft was then discussed with two experts from the Institute für Erziehungswissenschaft, University of Zurich; and then with the head of Education Outreach Group at CERN, Geneva, for ethical considerations. After these consultations, the semi-structured interview form was finalized and used during data collection.

Procedure

The procedure required the researcher to act as moderator to orchestrate the data collection process and increase coherence across the stages. This process started with the preparation of the interview agenda, which included details about the date, time, and venue of the focus group meeting, as well as the researcher's contact details. Following the agenda, the participants were provided with explanations for the following aspects: the motivation behind the study, the key topics to be explored, expected outputs (e.g., papers, further collaborations), and the importance of these outputs for the fields (e.g., who may need these outputs, how, and for what purposes?) The agenda was shared with the participants prior to the meeting, and they also received a reminder one day in advance.

The focus group meetings were conducted at CERN in a relaxed and informal environment to encourage the interviewees to express their thoughts freely and comfortably. The participants were provided with brief information about the process and questions at the start of the meeting, and they were given assurances of confidentiality. Individual permissions were also sought for the audio-recordings to ensure the data safety and reliability of later analyses. In a friendly scientific environment, the participants were encouraged to take the lead, direct the flow and manage the discussion processes. In addition to the audio-recordings, the researcher took notes based on her observations while encouraging participants to express their ideas in depth or move on to relevant discussions which were potentially important.

Data Analysis

The content analysis method was used to analyze the data. This method is useful in the sense that it allows the setting of a procedure to collect and organize data in a standardized fashion, which also enables the researcher to analyze the large amount of qualitative data systematically, enabling them to make inferences about the characteristics and meaning of the written and recorded material. The content analysis classifies textual material in line with the criteria of bringing together more relevant and manageable bits of data. As Smith and Eatough (2006) highlighted, formulating categories is the most crucial step in content analysis. The central idea in this formulation is that one or many words in the text can be classified as a category. The global themes are usually derived from research questions or key concepts. They can be elaborated on by categories (theme); each category contains codes, which represent particular sub-themes under them.

Following this pathway, the first step was to review the recordings and notes taken during the meeting, and then to consider what main themes had emerged. To assist with this process, the researcher transcribed the interviews (46 single-spaced pages), enabling her to add notes to the relevant sections and become acquainted with the data.

Initial classifications were derived from the research question. This enabled the researcher to code the data based on the meaning, rather than using sentence/word or paragraph-based coding. This thematic analysis followed Braun and Clarke’s (2008) step-by-step guidelines, namely (1) familiarization with the data, (2) initial code generation, (3) further immersion in the data through further reading of the transcripts, (4) definition of the themes, (5) naming and revising of the themes, and (6) reporting. Further details about the execution of these steps are as follows:

The researcher read the transcriptions again and again for familiarization and reviewed each sentence/idea with regard to its relevance to the research question. The transcriptions were then examined for possible coding categories. Care was taken in identifying frequently used expressions during this exploration; the expressions were cross-checked against each other by considering their meanings. On the other hand, when an unfamiliar expression was found, the previous expressions were re-evaluated.

During this exploration, the researcher used the left-hand margins on the transcriptions to take notes on anything that appeared significant and of interest. In the end, the researcher arrived at an initial list of codes for conceptual frameworks, research questions, hypotheses, problem areas, and key variables (see also Miles & Huberman, 1984, for the theoretical foundations of the approach).

The exploration process employed an open coding paradigm, enabling conceptual labels to be placed upon significant statements and then grouping these labels together to create initial categories (see Strauss & Corbin, 1990). The open coding technique required the transcripts to be inspected word-by-word and also sentence-by-sentence. Statements were clustered into categories and subcategories and they were reviewed against each other to assure that the categories and subcategories did not overlap with each other. This process was followed by the creation of the category list, and then the grouping of these under higher order headings. The aim of grouping the data enabled the researcher to reduce the number of categories by collapsing those that were similar or dissimilar into broader higher order categories. This process was repeated several times until the theme gathering process was completed.

The final review of the transcriptions intended to (a) refine the connections between the initial themes/categories, and (b) cluster them appropriately by taking into account the research question. These clusters, as global themes, were labeled to represent the conceptual nature of the themes they embodied. Therefore, the final list of global themes, categories, and subcategories emerged and was consolidated (see Table 2).

Validation Strategies

The study employed two kinds of robust validation strategy to ensure credibility and rigor: time triangulation, and multiple coding strategies. The time triangulation technique provided the researcher with the opportunity to overcome the risk of analyzing and assigning codes with and without a break: after completing the initial analysis, the researcher re-examined the above-mentioned thematic analysis once over three consecutive weeks of time. Note that each time the full scope of the analysis was re-examined. This technique was particularly useful in finalizing the themes and categories; and required a holistic view for the validation procedure. Secondly, a multiple coding strategy was employed to ensure reliability. Assigned codes, themes and categories were cross-checked by an independent researcher, and modified when it was necessary through an inter-rater reliability process (see Creswell & Miller, 2000; Creswell & Clark, 2011; Litosseliti, 2003).

Table 2: Themes and categories

Global themes	Categories	Sub-themes
1. Knowledge and experience	Background	
	Becoming an expert in the field	• Time • Essential steps
2. Particular learning paths	Colleague factor	• Richness of informal relationships • Establishing formal relationships
	Features of CERN	• Corporate structure of CERN • Working in an international environment
	Specific methods	• Measurement • Observation
	Recommendations	• Workshops • Letting students ask questions • Unearthing the imagination • Motivating them to find their own answers • Beyond the schools
3. New perspectives	Understanding	
	Daily life	
	Perceptions of reality	• Measurement • Uncertainty
4. A new language	Reasons	• Quantum theory • Indeterminism and probability • Language inadequacies
	Reflections	• Educational objectives • Curriculum • Interaction

Results

The qualitative analysis reported the views of the interviewees' directly (via direct quotations) and indirectly under the relevant categories and themes. Direct quotations ensured that the personal bias of the researcher was minimized in the analysis. This was demonstrated by bracketing, which represented self-awareness in the mindset of the researcher. From the analysis of the 46 single-spaced page transcription of the whole interview, four global themes and 11 categories emerged. These 11 categories also produced 21 sub-themes. The following section provides a list of the themes and categories obtained from the thematic analysis.

Knowledge and experience. The first global theme had two categories underneath, namely ‘background’ and ‘becoming an expert in the field’. Regarding ‘background’, the participants mostly talked about school effects (lecturers and courses), self-motivation and involvement in professional practices beyond the curriculum. They also criticized the school implementations they were exposed to. Some of the relevant quotations are:

> “*I think the underlying influence is coming from the high school, and the good teachers.” (P5)*
> *“Sort of physics I learned at school was boring stuff, the chemistry was a lie! They can't teach proper chemistry at the school level and biology I never trusted.” (P3)*
> “*Physics! It was absolutely boring, irrelevant, whatever word you can find. That was my school experience.” (P1)*

Under this global theme, the participants also pointed to two main ways of ‘becoming an expert in their field’: (a) time spent in the field - university as the most determining level for becoming an expert in the field; (b) essential steps -beyond the time dimension, various ways of becoming an expert were stressed, such as interacting with people (most mentioned), international collaborations, developing a good background, conducting experiments, working with students etc.

Particular learning paths. Under this global theme, participants explained their learning paths and resources under four categories: (a) colleague factor, (b) features of CERN, (c) specific methods, and (d) recommendations. Starting with the colleague factor, the participants mostly stressed the role of the richness of informal relationships, collective problem solving, asking questions without fear, sharing collective works, discussing research results, and e-mailing.

> *“I do learn from my colleagues. I learned from directly asking them if I know they are expert in a specific point.”(P4)*
> *“Personal interaction with more experienced colleagues is crucial.” (P5)*

The participants underlined that developing informal relationships with their colleagues is more effective than formal communications.

> *"... Usually, the lectures do not address exactly the questions you try to solve. When you work on a problem it's better to have an expert next to you and then try to solve the problem together."(P1).*
> *"A seminar is a way of a very low-level learning."(P3)*
>
> *"Being surrounded by different scientists has been the biggest impact on my way of thinking." (P6)*

The participants strongly stressed the importance of an international environment and stated that these kinds of environments provide them with unlimited and competitive interaction opportunities so that they can discuss their opinions with experts, free from borders or restrictions.

New perspectives. The third global theme emerged as 'new perspectives' with three categories underneath, namely (a) understanding, (b) daily life, and (c) perceptions of reality. All participants agreed that physics, in particular quantum theory, has been continuously changing various aspects of our lives. Classical physics played a major role in construing our everyday concepts. However, currently quantum theory pushes the boundaries and proposes a distinction in reality that revolutionizes our perception of it.

> *"Now we know there is something new there, reality is different to what we thought it is, it changed our world-view."(P3)*
> *"Physical reality today doesn't change. But our philosophical understanding of the physical reality of what's planted in the mathematical sense and the imagination absolutely does change."(P6).*

Although quantum theory refers to the microscopic world and does not seem to be relevant at a macroscopic scale, the participants stressed that we cannot understand the macroscopic world without knowing how the rules work at the quantum level. The impact of the quantum world is not limited to technological innovations though. According to the participants, any discovery in the microscopic world can change people's lives, predictably or unpredictably.

> *"Every lifeless thing in this room like a laptop is an example of the quantum mechanical device. We don't have an optical drive anymore. The transistor is also a quantum mechanical device." (P3)*

"For example, we can treat cancer with quantum physics: you're able to make lasers with quantum physics. You're able to have satellites orbiting the earth.
The GPS system uses special relativity, which you wouldn't have based on classical physics..."(P6)
"Atomic clocks, quantum computers, lasers... The lasers are basically a product of new physics. Our understanding of subatomic particles and their interactions could never come up with classical physics."(P5)

On the other hand, the dilemma of the struggle between the body and mind is crucial: we as people can use our imaginations to an extent, but our bodies like stability and concrete evidence, as we are used to living in a three-dimensional world with set rules. It may be too difficult for the human brain to then perceive and believe in the idea of extra dimensions, which are studied within the new physics.

"*What many people believe to be physical reality is just an illusion of our senses. It doesn't exist really. I would go as far as saying; nobody really knows what physical reality is... And, what you observe there you have no intuitive imagination for. So you believe there is something solid but there isn't. Solidity of the matter comes only from the strange fact that two electrons don't like to be at the same place at the same time... Physical reality is very different from what people believe it is."(P1)*

New language. The last global theme produced two categories: (a) reasons, and (b) reflections. Regarding the reasons, four out of the six participants agreed on the necessity of a new language. The reason for this necessity was explained by three sub-themes, namely quantum theory, indeterminism and probability, and inadequacy of natural languages.

"The equations of quantum physics and its mathematical framework are very different to classical mechanics."(P3)
"A new language has been developing since 1920 and 1930."(P1)
"*Quantum mechanics! You have to think in a different way."(P6)*

The distinction between uncertainty and determinism, and the probabilistic nature of quantum phenomena were the other referenced sources of this necessity.

"The wave-particle duality, the description of the fundamental laws of nature using quantum physics and relativity, has really been forced

upon us by the developments and that also requires a common way of thinking."(P1)

"Certainly, in modern physics, we have to think in a different way. If we now think everything is probabilistic, ultimately everything is just two particles interacting, or multiple particles interacting."(P3)
"The difference between the classical way of thinking where you can determine everything and also the quantum approach where you basically formulate your problem using probabilities."(P5)

Three participants emphasized communication problems arising from inadequacies in natural language.

"It is really hard to communicate and grasp the facts when we talk about subatomic particles."(P5)

Another participant addressed the jargonized nature of their language, and explained the distinction between jargonized and everyday language.

"Certainly, there is a jargon of science. We have to be very careful when we talk to the public that they don't misunderstand us. We talk about the top quark, and the color. Color means nothing; has nothing to do with the color that we see right now. They are completely different. Certainly, somebody who is not a scientist wouldn't be able to understand what we are saying. (P3)

The last category was 'reflections'. Regarding this, the participants proposed that new physics has impacts on many disciplines ranging from computer science to statistics and neuroscience, and the impacts are certainly not restricted to educational sciences.

The participants also underlined some issues related to educational objectives, curriculum and interaction techniques. Primarily, two participants pointed out perception problems with regard to educational objectives.

"It is much more important to teach and to put it into a cosmic frame than to learn some irrelevant laws, which you usually learn in physics. We have too much nationalism and too much short-sightedness in schools."(P1)
"The first thing is to let us, people, have a broader perspective. Learning from physics will teach you that whatever you know to be true today might be wrong tomorrow, like a misunderstanding of the concept. What you teach to our kids today might not be correct tomorrow."(P5)

Curriculum and program development areas were seen as more crucial.

> *"In some sense you do not want to teach a picture of the world which is not correct."(P1)*
> *"If we change our way of thinking and understanding about what surrounds us, this may have impacts on curricula."(P4)*
> *"Certainly, at least in my days, at school it was all very dull, kind of old-fashioned physics. And the interesting stuff you only learn in University."(P3)*

Collective work is necessary between experts from both fields, and interactions should be mutual. Educationalists should work with experts, such as physicists, when it comes to changing/organizing the curriculum and physics content.

> *"If education people interact more with physicists, it will be easier to grasp these new developments to explain to their students. Because what we are teaching today might not be optimal, and if we know that this is not optimal today we shouldn't wait for another 10 years to teach this to our kids."(P5)*

Consequently, the notion of education, its objectives, curriculum development, and mutual interactions were the most crucial categories within this theme. The participants also stressed that students' learning should be the priority beyond teaching laws and rules.

Discussion

This study revealed that despite the large dissimilarities between the two fields, physicists have some unique suggestions to offer educationalists, as discussed below. The participants agreed on the first research question (can the experiences of the physicists at CERN be transformed into education?), and they underlined the need for a close collaboration aiming to improve the ways in which physics is introduced and supported in schools from early years of education. It seemed meaningful that four out of the six participants criticized the current educational implementations in the countries they were involved in. They highlighted the role of exceptional teachers and that specific courses made them want to pursue their careers in this field. However, despite these encouraging factors, science, particularly physics teaching in high school was defined as inadequate, short-sighted about the mysteries of the universe, and thus fell short in developing their understanding of relevant topics. Instead, they needed to be able to focus on the specific literature more deeply and freely; receive more encouragement for their curiosity, and to use scientific methods in their learning; this should have been reflected in the assessment methods they were exposed to.

Most criticisms targeted the educational practices and the curriculum. A cartoon portrayed their view about the educational practices in school settings: “There is a guy sitting behind a table and there are different animals in front of him, ranging from a fish in a bowl to an elephant. He says, well, we need to be fair to everyone, so we are going to take an exam; everybody has to climb this tree… Of course, the fish couldn’t climb the tree; but the monkey did it easily. The elephant destroyed the tree...” This story suggested a meaningful analogy about the consequences if educators do not take their students’ individuality into account.

While some students needed more supportive environments to deepen their knowledge in topics, they wanted to learn more of, schools were criticized as failing to provide this support, particularly in national and international collaboration platforms to satisfy students’ needs. Getting in touch with others at international platforms was seen to be crucial for the learning journey and participants stated that schools did not provide enough support for their educational needs either.

Almost all participants stated that "learning to learn" is an imperative in science; and therefore, learning and exploring are the most important components of science education that children need to practice from very early on. This process never ends; once they gain more experience and deepen their knowledge, they continue to learn from colleagues, which is an informal and effective way of fast idea sharing. Science is always about racing against time, and therefore requires its practitioners to perform such acts in a limited period of time. Fostering imagination, curiosity, abstract thinking, group works/workshops focusing on specific subjects; letting learners ask questions; motivating them to find their own answers, and encouraging free thinking are highlighted as crucial for all levels and ages as forming the habit of learning to learn.

One idea was unique, namely inferential comprehension as explained below: learners must first consider the available explanations for their questions. However, although learning from previous work is crucial, they should synthesise their own truths rather than acknowledging an existing model without questioning it. The ability to question others’ models is crucial for collective problem solving, team working, as well as asking more specific questions to progress the theory further. Although we do not expect secondary school children to immerse themselves in literature and then understand complex physical theories corresponding to their questions afterwards, this point can be seen as a stance against the common classroom teaching practices where ready-made knowledge is transferred in a unidirectional way. The ideas behind inferential comprehension would lead to discouraging schools from stipulating the reading of many books, following the course content, or searching via the internet which results in promoting learners’ reliance on existing knowledge. This implies that using pre-digested knowledge prevents students from trying, testing, or relying on their observation skills in finding and creating their own answers, and impacts on their attitude towards their own ideas, creativity, and competences. Slavishly following the ideas that are laid out in course books also negatively influences inferential comprehension. What is recommended instead is focusing on specific topics, reading from different perspectives, asking specific questions, refining the ideas, and testing/measuring them each time in a scientific manner. Therefore, inferential comprehension is a process allowing the learners to feel more like sculptors who are constructing new possibilities out of already existing knowledge.

Study 2

This study utilized a quantitative paradigm, which works in an opposite direction and explores population level beliefs/understandings. The research arrived at this phase from an exploratory stage in which qualitative data were initially collected and analyzed (see Teddlie & Yu, 2007, for the methodological foundations). The details of this study can be found in Dündar-Coecke (2014). The aim here is to show how population level outcomes were consistent with the results obtained from the first study.

Participants

The study recruited 108 participants from across 25 countries working at CERN, who completed the questions in the 'Philosophical Impacts of New Physics on Educational Sciences' (PINPE) questionnaire.

The participants varied depending on the experiment groups they were involved in, ranging from theoretical physics to experimental. The theoretical subfields ranged from antimatter, astroparticle physics and string theory to quantum field theory (n = 37, 34.3%). The name of the experiment groups and the distributions were: ALICE (n=12, 11.1%), ATLAS (20, 18.6%), ALPHA (6, 5.5%), CAST (5, 4.6%), CMS (15, 13.9%), LHCb (9, 8.3%), TOTEM (4, 3.7%). Therefore, 34.3% of the participants represented the theoretical division, while 65.7% of them represented 7 different experiment groups. Their number of working years in the field varied from 3 to 26 years.

Materials and procedure

The questionnaire –PINPE– was structured by the researcher on the basis of the qualitative results, aimed at focusing on qualitative results concisely. The survey questions were composed with the aid of the preliminary thematic analyses, were reviewed by two colleagues for a further reliability check, and further permissions to use PINPE were obtained from experiment group coordinators or managers, who also commented on the questionnaire. The survey took a maximum of 10 minutes to complete.

Analysis

The data were analyzed by using chi-square, as well as frequency distributions. The chi-square analysis was evaluated with a 95% confidence level.

Results

Apart from the demographic questions, four questions were analyzed, each organized independently. Regarding the first question, 95 (88.8%) participants agreed with the statement "New physics forces us to change our view of physical reality" without significant differences regarding their working groups ($\chi2 = 1.634$, df = 2, $p>0.05$), or their experience in the field ($\chi2 = 6.256$, df = 4, $p>0.05$).

For the second question, 96 (88.9%) participants agreed with the statement that "Developments in quantum theory have been revealing the need for new ways of thinking" without significant differences regarding their working groups ($\chi2 = 0.253$, df = 2, $p>0.05$), or experience in the field ($\chi2 = 4.001$, df = 4, $p>0.05$).The third question was, "Which of the following fields in educational science might have been influenced by developments in physics?" Respondents were provided with a multiple-choice question that allowed them to select more than one response. In total, 87 (80.6%) participants chose curriculum (what we teach); while 58 (53.7%) of them pointed to the field of measurement and evaluation (what is learned); 48 (44.4%) of them referred to teaching-learning techniques (how and where we teach); 41 (38%) of them pointed to targets of education (why we teach); and 20 (18.5%) of them chose the field of psychology (helping one's self-realization). For the curriculum, there was a significant association between response and the working groups ($\chi2 = 5.050$, df = 1, $p<0.05$), as 73.5% of experimentalists, and 91.9% of theorists thought that the curriculum has been influenced by recent developments in physics. However, we need to acknowledge that the participation rate of the experimentalists was significantly lower than theorists for this question.

The last question was "Do developments in physics provide new paradigms for education?" In total, 71 (66.4%) participants expressed a positive opinion, while 36 (32.6%) of them indicated a negative opinion. Chi-square test results were not significant, neither for the working groups ($\chi2 = 0.781$, df = 2, $p>0.05$), nor working year in the field ($\chi2 = 4.277$, df: = 4, $p>0.05$).

Discussion

The second study was aimed at answering the question "To what extent do developments in quantum physics have an impact on educational practices?" Through a population level analysis, the results showed that most physicists agreed with the idea that the developments in physics, particularly in quantum theory, have some practical and theoretical implications on education sciences. For instance, the vast majority of the participants thought that new developments in quantum physics should be discussed with children as early as possible, as it contributes to their understanding of the Newtonian paradigm and inspires their thoughts on physical reality, and also fosters philosophical and scientific insights on whether the need for new ways of thinking is necessary. Such a view contrasts with any approaches suggesting the existence of an absolute truth in education.

The study also highlighted the notion that physical reality does not change but instead our understanding and imagination of it changes. The Copenhagen interpretation can be seen as an attempt to provide the philosophical grounds for this view as initially discussed by Bohr (1958) and Heisenberg (1958). According to Bohr, for instance, objective knowledge is constituted in experienced space when the subject places phenomena in causal connection across space and time. Objective reality therefore is highly dependent on sensorial experiences, where the necessary concepts such as space, time, momentum and energy are present as preconditions of human knowledge, giving us the opportunity to talk about objective reality. According to Heisenberg (1955, 1958), the difficulty arises when one is required to express quantum formalisms with ordinary language. The inadequacy of natural language becomes apparent when it comes to speaking about technical terms in physics, such as atoms or nuclear physics: there is no way of really knowing in the classical sense what words like 'momentum' and 'wave' mean when applied to quantum events. Consistent with this, in the first study, some participants mentioned the necessity of more abstract language to deal with the highly abstract nature of phenomena. Some of them did not agree but suggested an enhancement in natural language through a constant production of scientific jargons, new words, or symbols. Although the role of language is beyond the focus of this study, we can expect the difficulties in teaching complex quantum formalisms to double up if even experts find natural language as being unrepresentative of high-level thinking. This can explain how other forms of communication, such as mathematical language, or other abstract forms of expression, compensate for this gap. However, the unique language of quantum formalism is still debated (see Coecke et al., in preparation).

The majority of participants indicated that curriculum is the most influenced subfield in education. It was followed by the field of measurement and evaluation. This suggests that two strongly connected questions, what we teach and what is learned, are crucial from the participants' perspective. This result is also consistent with the qualitative results where the participants criticized the school systems and described curricula with irrelevant subjects. In the literature, similar discussions can be found in Hurd's (1991), Vella's (2002), Rush et al.'s (2014), Brookes's (2006), and Pospiech's (2010) studies, each underlying various issues in curricula. The analyses here added to these discussions that participants' years of experience did not influence the result, suggesting that criticisms were consistent across different generations. A difference was seen between the theoretical and experimental physicists in the sense that theoretical physicists believed more strongly that the curriculum has been influenced by recent developments in physics.

DISCUSSION AND CONCLUSIONS

Combining two kinds of research paradigm, the outcomes from both studies highlight that recent developments in quantum physics have possible impacts on education from the point of view of physicists.

In terms of interactions, the most relevant subfields were seen as program development, teaching and learning. Regarding the first, although the samples included many physicists from various countries, their criticisms were similar: they stated that most topics in syllabi are irrelevant, boring, or inadequate for understanding the field and by extension physical reality and the universe. In one way, this result resonates with the teaching and learning subfields outcomes. For instance, Pospiech (2010) and Drummond (2019) highlight the lack of consensus on the didactical aspects of teaching quantum theory; and also, the difficulties in understanding and implementing the new methods that support mathematical and non-mathematical aspects of this particular language. The challenge broadens when teachers have to follow a predetermined curriculum supported by school books that often approach quantum physics in a traditional way. These results justify why the above-mentioned studies on physics education are pertinent, and why it is worth trying various innovative methods via research-based approaches in classroom settings.

Consistent with that, Hurd (1991) notes that modern science changes rapidly, and the way theories are organized in quantum theory is yet to be reflected in science curriculum. According to Sizer (1984) the difficulties arise from the fact that learning theories embodied in school systems are designed for teaching large numbers of students and this is achieved through the standardized curriculum approaches all around the world. Targeting this large number of students seems to be the wrong approach, as many students fail to develop a complete understanding of the relationship between classical and quantum mechanics during a typical quantum mechanics course (see Crouse, 2007). Research elaborates on further difficulties that cripple the teaching of quantum theory in classroom settings and proposes various solutions to overcome this Newtonian influence on education (Vella, 2002; Rush et al., 2004; Dong et al., 2006). A non-Newtonian curriculum is proposed to equip students with the required skills to deal with the chaotic and uncertain nature of this theory, with the aim of fostering critical thinking, reflective intuition, and problem solving skills (Slattery, 2013).

Overall, the participants proposed unique suggestions that could be useful for educationalists when they deal with the highly abstract nature of phenomena in school settings.

- What we teach, how we teach it, why we teach it and where are fundamental questions, and experts have a significant number of criticisms regarding all of these, as this research revealed.
- *Inferential comprehension* can be embedded in teaching as discussed at the end of the first study.
- Exceptional teachers can change students' educational and vocational pathways.
- Students should also demonstrate strong self-control over their career pathway, rather than being passively carried along by school implementations.
- The importance of close collaboration between teachers and field specialists was emphasized as a strategy to cope with slow improvement in school science.
- More frequent and fast interactions between physicists and educators are necessary to improve science teaching.

This is the first study transferring physicists' voices to educationalists using an analytic method. Given that ideas and educational issues require specific and general domain knowledge, more interdisciplinary research is needed where teachers, and even students, can take part. In fact, a recent study (Dündar-Coecke, 2020) showed that older than 14-year-old students largely agreed with physicists, claimed more independence in their science learning and showed high motivation for self-directed learning. The generalizability of these results in both communities needs further investigation. For instance, further research can survey educationalists' views on the same matter. Another follow up can also focus on concrete solutions and the recommendations of physicists, in particular as to what would be taught, at which level students can be introduced to the quantum world, and what kind of models are needed to train young thinkers.

REFERENCES

Braun, V., & Clark, V. (2008). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77-101.

Bohr, N. (1958). *Atomic physics and human knowledge*. New York: Willey.

Brookes, D.T. (2006). The role of language in learning physics. Unpublished dissertation State University of New Jersey, USA.

Cantley, I. (2015). How secure is a Newtonian paradigm for psychological and educational measurement? *Theory & Psychology*, 25 (1), 117-138.

Chabay, R.W., & Sherwood, B.A. (2015). *Matter and interactions*. New York: Wiley.

Coecke, B., Gogioso, S., Kissinger, A., Pfaendler, S., Dündar-Coecke, S., & Khan, I. (in preparation). *Quantum theory in pictures*.

Creswell, J.W. (2005). *Educational research: Planning, conducting, and evaluating quantitative and qualitative research*. USA: Pearson Prentice Hall.
Creswell, J.W. (2014). *Research design: Qualitative, quantitative, and mixed methods approaches*. Sage.
Creswell, J.W., & Clark, V.L. (2011) *Designing and conducting mixed methods research*. Sage
Creswell, J.W. & Miller, D.L. (2000). Determining validity in qualitative inquiry. *Theory into Practice*, 39, 124-130.
Crouse, A.D. (2007). *Research on students' understanding of quantum mechanics as a guide for improving instruction*. Unpublished dissertation, University of Washington.
Dong, D., Chen, C., Zhang, C., & Chen, Z. (2006). Quantum robot: Structure, algorithms and applications. *Robotica*, 24, 513-521.
Drummond, B. (2019). Understanding quantum mechanics: A review and synthesis in precise language. *Open Physics*, 17, 390-437.
Dündar, S. (2012). *Eğitimde bilim teorisi.* Nobel.
Dündar-Coecke, S. (2014). Ramifications of quantum physics for education. *Problems of Education in the 21st Century*, 58(58), 53-66.
Ernest, P. (1997). The epistemological basis of qualitative research in mathematics education: A postmodern perspective. *Qualitative Research Methods in Mathematics Education*, 9, 22-177.
Fraser, J.M., Timan, A.L., Miller, K., Dowd, J., Tucker, L., & Mazur, E. (2014). Teaching and physics education research: Bridging the gap. *Reports on progress in physics*, 77(3): 032401.
Gawlik, K. (2017). Focus group interviews. In M. Ciesielska & D. Jemielniak (Eds.), *Qualitative methodologies in organization studies: Methods and possibilities* (pp. 97-126). Switzerland: Palgrave Macmillan.
Gray-Donald, J. (2007). Implications of quantum theory on education: a critical review of the literature. *International Journal of Innovation and Sustainable Development*, 2(3/4), 315-331.
Heisenberg, W. (1955). The development of the interpretation of the quantum theory. In W. Pauli (Ed), *Niels Bohr and the development of physics* (pp. 12-29). London: Pergamon.
Heisenberg, W. (1958). *Physics and philosophy: The revolution in modern science*. New York: Harper Row.
Henriksen, E.K., Bungum, B., Angell, C., Tellefsen, C.W., Fragat, T., & Vetleseter Boe, M. (2014) Relativity, quantum physics and philosophy in the upper secondary curriculum: Challenges, opportunities and proposed approaches. *Physics Education*, 49(6), 678.
Hunter, W.J., & Benson, G.D. (1997). Arrows in time: The misapplication of chaos theory to education. *Journal of Curriculum Studies*, 29, 87-100.
Hurd, P.D. (1991). Why we must transform science education? *Educational Leadership*, 49 (2), 33-35.
Johnston, I.D., Crawford, K., & Fletcher, P.R. (1998). Student difficulties in learning quantum mechanics. *International Journal of Science Education*, 20(4), 427-446.

Krijtenburg-Lewerissa, K., Pol, H.J., Brinkman, A., & van Joolingen, W.R. (2017). Insights into teaching quantum mechanics in secondary and lower undergraduate education. *Physical Review Physics Education Research*. DOI:10.1103/PhysRevPhysEducRes.13.010109.

Koopman, L., Brouwer, N., Heck, A., & Buma, W.J. (2008). Remedial mathematics for quantum chemistry. *Journal of Chemical Education*. 85, 1233-1236.

Krueger, R. (1994). *Focus groups: A practical guide for applied research*. USA: Sage, Thousand Oaks.

Kuhn, T.S. (1962). *The structure of scientific revolutions*. USA: University of Chicago Press.

Litosseliti, L. (2003). *Using focus groups in research*. London, UK: Continuum Publishing.

Mason, M. (2008). Complexity theory and the philosophy of education. *Educational Philosophy and Theory*, 40, 4-18.

Mazur, E. (1997). *Peer instruction: A user's manual*. Upper Saddle River, NJ: Prentice Hall.

Maxwell, J.A. (1997). Designing a qualitative study. In L. Bickman and D. J. Rog (Eds.), *Handbook of applied social research methods* (pp. 69-100). USA: Sage, Thousand Oaks.

Michelini, M., Ragazzon, R., Santi, L., & Stefanel, A. (2000). Proposal for quantum physics in secondary school. *Physics Education*, 35, 406-410.

Miles, M.B., & Huberman, A.M. (1984). *Qualitative data analysis: A sourcebook of new methods*. USA: Sage, Thousand Oaks.

Millward, L. J. (2006) Focus groups. In G. M. Breakwell, S. Hammond, C. Fife-Schaw & J. A. Smith (Eds.), *Research methods in psychology* (pp. 274-298). London: Sage.

Morgan, D.L. (1993). *Successful focus groups: Advancing the state of the art*. USA: Sage.

Morrow, S.L. (2005). Quality and trustworthiness in qualitative research in counseling psychology. *Journal of Counseling Psychology*, 52 (2), 250-260.

Papaphotis, G., & Tsaparlis, G. (2008). Conceptual versus algorithmic learning in high school chemistry: The case of basic quantum chemical concepts. Part 2. Students' common errors, misconceptions and difficulties in understanding. *Chemistry Education Research and Practice*, 9(4), 332-340

Patton, M.Q. (1990). *Qualitative evaluation and research methods*. USA: Sage, Thousand Oaks

Popper, K.R. (1951). Indeterminism in quantum-mechanics and in classical physics. *The British Journal for the Philosophy of Science* 1(2), 117-133.

Popper, K. R. (1982). *Quantum theory and the schism in physics: From the postscript to the logic of scientific discovery*. London: Hutchinson.

Popper, K. R. (2002). *The logic of scientific discovery*. Oxford, UK: Routledge.

Pospiech, G. (2010). *Teaching quantum theory: Between the photoelectric effect and quantum information*. Paper presented at the conference of the GIREP08 https://pdfs.semanticscholar.org/41b6/abdd846856e7aeee55e43f9842741c96a2f9.pdf.

Reigeluth, C.M. (2008). Chaos theory and the sciences of complexity: foundations for transforming education. In B. Despres (Ed.), *Systems thinkers in action: A field guide for effective change leadership in education*. New York: Rowman & Littlefield.

Rush, K.L., Peel, K., & McCracken, B. (2004). Empowered learning on the inside: An externship experience. *Nursing Education Perspectives*, 25 (6), 284-291.

Savin-Baden, M. (2008). *Learning spaces: Creating opportunities for knowledge creation in academic life.* Maidenhead: McGraw Hill/Society for Research into Higher Education & Open University Press.

Sizer, T.R. (1984). *Horace's compromise: the dilemma of the American high school*. Boston: Houghton Mifflin.

Slattery, P. (2013). *Curriculum development in the postmodern era: Teaching and learning in an age of accountability*. London: Routledge.

Smith, A.J., & Eatough, V. (2006). Interpretative phenomenological analysis. In G.M. Breakwell, S. Hammond, C. Fife-Schaw & J.A. Smith (Eds.), *Research methods in psychology* (p. 322-341). London: Sage.

Steils, N., Tombs, G., Mawer, M., Savin-Baden, M., & Wimpenny, K. (2014). Implementing the liquid curriculum: The impact of virtual world learning on higher education. *Technology, Pedagogy & Education*, 24(2), 155-170.

Strauss, A.L. (1987). *Qualitative analysis for social scientists*. Cambridge: Cambridge University Press.

Strauss, A.L, & Corbin, J.M. (1990). *Basics of qualitative research: Grounded theory Procedures and techniques*. USA: Sage, Thousand Oaks.

Teddlie, C., & Tashakkori, A. (2009). *Foundations of mixed methods research: Integrating quantitative and qualitative approaches in the social and behavioral sciences*. USA: Sage, Thousand Oaks.

Teddlie, C., & Yu, F. (2007). Mixed method sampling: A typology with examples. *Journal of Mixed Methods Research*, 1, 77-100.

Vella, J. (2002). Quantum learning: Teaching as dialogue. *New Directions for Adult and Continuing Education*, 93, 73-84.

Vokos, S., Shaffer, P.S., Ambrose, A.S., McDermott, L.C. (2000). Student understanding of the wave nature of matter: Diffraction and interference of particles. *American Journal of Physics*, 68, 42-51.

Watkins, J., & Mazur, E. (2013). Retaining students in science, technology, engineering, and Mathematics (STEM) majors. *Journal of College Science Teaching*, 42(5), 36-41.

SELMA DÜNDAR-COECKE, PhD, is a reader in education and holds a second PhD degree in educational neuroscience. Her major research interests lie in the area of science learning, causal cognition, and alternative education. Email: selma.coecke@gmail.com

Manuscript submitted: ***May 6, 2020***
Manuscript revised: ***December 16, 2020***
Accepted for publication: ***April 5, 2021***