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FOSTERING STUDENTS’ CONCEPTIONS ABOUT THE QUANTUM WORLD – RESULTS OF AN INTERVIEW STUDY

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STRUCTURED ABSTRACT

Background: Quantum physics is both a highly topical and challenging topic of physics education. Learning quantum physics is inherently difficult because it is unimaginative, counterintuitive and fundamentally different from what learners know from their everyday life and classical physics. The results of recent studies underline that students are often not aware of the relevance of quantum physics and its technologies for their own lives, which makes studying quantum physics even more difficult. This is the starting point of this article: With the Erlanger teaching concept, we present an introductory teaching concept for quantum physics at secondary schools with the aim, among others, to raise students’ awareness of the importance of modern quantum technologies today and in the future.

Purpose: In order to evaluate which conceptions about the quantum world arise among students who are introduced to quantum physics with the Erlanger concept, we conducted an interview study.

Sample/Setting: A random sample of $N = 25$ students was interviewed after the intervention (15 male, 10 female) in order to answer the questions mentioned above. The interviews had a duration of 25 – 40 minutes. Prior to the intervention, none of the students had any classroom instruction in quantum physics.

Design and Methods: The students’ answers were transcribed and then evaluated on the basis of deductive and inductive categories using qualitative content analysis. The coding was done by independent coders ($\kappa = 0.84, 95\% - CI$ $[0.68; 1.00]$). Additionally, a cluster analysis was performed and a three-cluster solution was extracted. The three clusters could be interpreted in terms of content and thus facilitate the characterization of occurring types of students’ conceptions after the intervention.

Results: After the intervention with our concept, we found elaborated conceptions about the quantum world with the majority of respondents. 11 of the 25 students (cluster 1, labelled *Primarily elaborate conception*) are aware of the striking differences between quantum and classical physics, as all students in this cluster characterize the quantum world via effects or aspects that do not exist in classical physics. The importance of quantum physics for future technologies was named by the students combined in the cluster 2, labelled *Quantum world as the world of technology*. 10 of the students interviewed (cluster 3, labelled *Quantum world as a classical world on a small scale*) seem to stick to their pre-conceptions dominated by classical ways of thinking.

Conclusions: Our article provides implications for both classroom practice and future research. For classroom practice, the Erlanger teaching concept serves as a proposal to bridge the gap between quantum physics and the everyday life of the learners. In addition, the results of the interview study presented in this paper make a contribution to the empirical research on students’ conceptions about quantum physics. We not only find individual, independent conceptions of learners, but we also show that there are dependencies between them, allowing us to extract types of conceptions. The extraction of such types of student conceptions for various further concepts of quantum physics will be part of future research and could contribute to our understanding of learning processes in quantum physics.

Keywords: *quantum physics, interview study, cluster analysis, teaching concept*

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1 INTRODUCTION

Quantum physics is both a highly topical and challenging topic of physics education. Studying quantum physics is inherently difficult because it is unimaginative, counterintuitive and fundamentally different from what learners know from their everyday life and classical physics. Scholz et al. (2020) speak of a "knowledge reboost" that is required for learning quantum physics.

In order to make such a reboost possible, learning difficulties in quantum physics must be known. While recent studies contribute significantly to our understanding of the learners’ model understanding in quantum physics (Ubben & Heusler, 2019) and our understanding of patterns of student difficulties in modern quantum physics in schools (Marshman & Singh, 2015), the learner's perspective on learning about quantum physics remains unknown so far: A first study on the importance of learning quantum physics from the perspective of secondary school students revealed that students are often not aware of the relevance of quantum physics and its technologies for their own lives (Moraga-Calderón et al., 2020). Moraga-Calderón et al. (2020) therefore conclude that a stronger link between quantum technologies or physics and the daily life of students must be established in the teaching of quantum physics. Teaching quantum physics must therefore be motivated in terms of content by modern aspects of quantum technologies as they influence the social lives of students today, and will do so even more in the future - it is not without reason that the European Quantum Flagship initiative advertises its cause with the slogan "The Future is Quantum" (EU, 2019).

We are taking up this point with this article: with the Erlanger teaching concept for quantum physics (chapter 2 of this article), we make a proposal how modern quantum physics can be taught in schools. This concept is motivated by and connectable to the basics of quantum technologies. In chapter 3 and 4 of this paper, we report the results of an explorative interview study on clusters of students' conceptions that might be formed about the quantum world, introducing students (without prior knowledge) to quantum physics using the Erlanger concept: By means of cluster analysis, we were able to extract preliminary types of students' ideas about the quantum world. The results suggest that the Erlanger teaching concept for quantum physics makes it possible to explain the importance of quantum technologies in secondary schools, and thus to create an awareness among learners of the importance of modern quantum technologies for their everyday life today and in the future.

2 THE ERLANGER TEACHING CONCEPT OF QUANTUM PHYSICS

2.1 Design principles

The Erlanger teaching concept on quantum physics forms a proposal for teaching quantum physics at the secondary school level (11th/12th grade). The underlying design principles were derived from literature concerning research on quantum physics education, specifically including the following four perspectives:

1. **Content perspective on the status quo of teaching quantum physics in school:** Stadermann et al. (2019) derived an international core curriculum for quantum physics in schools from a review of 15 different national physics school curricula and summarised the status quo in terms of content for today's quantum physics teaching. In another article, Krijtenburg-Lewerissa et al. (2018) used a Delphi study to investigate the question of which quantum physics topics should be taught in quantum physics classes at secondary schools from an expert's perspective. Both cited research papers are in accordance regarding two key points: first of all, quantum physics in school today is predominantly taught by historical approaches and topics, such as wave-particle duality which is seen quite critically, because aspects of modern quantum physics remain underrepresented. Consequently, as a second key point, both call for research into the feasibility of integrating modern findings of quantum physics into physics lessons at school, far beyond wave-particle dualism – and this demand is not new at all. The proposal to avoid historical approaches in introductory quantum physics curricula was already put forward in a contribution by Brachner and Fichtner as early as 1974 (Brachner & Fichtner, 1974).

   From a content perspective, the Erlanger teaching concept is therefore based on the following design principle: Provide modern insights into quantum physics, avoiding historical approaches.

2. **Learning difficulties in quantum physics:** A general overview of the current state of physics education research on learning difficulties in quantum physics is provided in the review article published by Krijtenburg-Lewerissa et al. (2017). Frequently reported learners' difficulties are based on mechanistic ways of speaking and thinking, e.g. students think about electrons as haptic particles or about photons as bright balls with a permanent location (Masshadi & Woolnough, 1999; Mannila et al., 2002; Hubber, 2006). These make it difficult to build up quantum physics-based conceptions (Müller & Wiesner, 2002).

   Thus, taking into account results from research into students' difficulties in quantum physics, the Erlanger concept is based on the following design principle: Introduce quantum physics in a way that is detached from mechanics.

3. **Teachers' perspective:** In recently published results of a Delphi study into teachers' needs for teaching quantum physics in the classroom (Weber, Friege & Scholz, 2020), three points are crucial: firstly, the authors report on the teachers' need for quantum physics experiments (esp. with single photons) for classroom practice, or at least for simulations or animations. Secondly, these experiments are supposed to reveal the characteristic traits of quantum physics as formulated by Küblbeck and Müller (2003) from the teachers' point of view. And thirdly, teachers attach great importance to the practicality of the material provided. The criterion of *practicality* is difficult to fulfill with today's real experiments with individual quantum objects at schools (Kral et al., 2016), but interactive screen experiments on single photons are accessible (Bronner et al., 2009).

   Thus, the Erlanger concept is based on the following design principle: Integration of interactive screen experiments from quantum laboratories leading to the characteristic traits of quantum physics.

4. **Learners' perspective:** A study published in 2020 investigated the importance that students attach to learning about quantum physics (Moraga-Calderón et al., 2020). The key finding of the study was that while learners considered quantum physics important for society, they did not equally recognise the relevance of quantum physics to their own lives. In their summary, the authors conclude that students should be taught the importance of applications of quantum physics for society and for their everyday lives.

   Thus, the Erlanger concept is based on the following design principle: The new concept on quantum physics must be motivated by modern aspects of quantum physics as they influence the social lives of learners today, and even more so in future.

2.2 Key ideas of the Erlanger teaching concept

The design of the Erlanger teaching concept takes into account the requirements derived from the literature (chapter 2.1). Table 1 shows how they are addressed in the design of the new concept: in a Delphi study, physics teachers expressed a need for experiments in quantum physics classes (Weber et al., 2020). Especially, single photon experiments, among others, proved to be thematically interesting for teachers.

The treatment of single photon experiments in class is in accordance with

1. the requirement not to introduce quantum physics as an extension or generalisation of classical mechanics, so that mechanistic ways of speaking become superfluous in quantum physics lessons and
2. the requirement to include modern quantum physics in schools.

In this way, quantum physics is formulated as an extension of classical optics instead of as an extension of mechanics, using the quantum object photon as an example. The treatment of quantum physics with single photon experiments thus leads to a doctrine of quantum physics that is founded in optics - quantum optics (Bitzenbauer & Meyn, 2020a).

The key ideas used in the Erlanger concept are as follows:

- Prevention of mechanistic ways of speaking and thinking: the avoidance of wave-particle dualism from teaching quantum physics makes a discussion about the mechanistic trajectories in quantum physics redundant, and the meaning of the property *position* in quantum physics is addressed in the context of measurement.

- Notion of preparation instead of transmitter-receiver-concept: instead of talking about photon sources, the preparation of quantum states by coincidences is emphasized.

- Highlighting effects that cannot be explained semiclassically: Data from quantum optics experiments are used to understand the quantum nature of light.

- Talking about photons: emphasis on the model character, esp. on the QED model (Jones, 1991), defining photons as elementary excitation of the electromagnetic field.

2.3 The new curriculum

Modern quantum technologies, such as quantum computing, quantum cryptography and so forth, exploit the control and manipulation of individual quantum objects, e.g. single photons. As an introduction to the teaching concept, a self-developed explanatory video is shown (Donhauser, Bitzenbauer & Meyn, 2020). The explanatory video motivates to deal with quantum objects and phenomena using the examples of quantum computers and data security and thus incorporates the significance of quantum technologies for the students' lives from the very beginning: The importance of data security is discussed with the students beforehand and the influence of quantum physics on data security is addressed in the explanatory video.

In order to lay the foundations for understanding modern quantum technologies with the students, the Erlanger concept deals with the essential traits of quantum physics (Küblbeck & Müller, 2003) using single photon experiments in interactive screen experiments (Bronner et al., 2009) based on the experiment from the publication of Grangier et al. (1986).

Tab. 1. Requirements for a new teaching concept on quantum physics derived from literature and their implementation in the Erlanger concept of quantum physics.

Requirement from literature review (chap. 2.1)	Implementation in the new concept with/by…
1. Integration of modern quantum physics	Single photon experiments leading to a QED model of photons
2. Detach quantum physics from classical mechanics	Introduction into quantum physics from classical optics
3. Explain characteristic traits of quantum physics with real experiments, simulations or animations	Providing interactive screen experiments and adaptable working material
4. Emphasis on importance of quantum technologies	Starting point data security / quantum computers

With this experiment, the indivisibility of photons (anti-correlation effect) as well as single photon interference can be shown simultaneously. The results of this experiment mean that the idea of the photon as a localized particle must be dropped. In this way, a transition from classical to quantum physics is made possible.

The concept can be carried out in four lessons (90 min. each):

Chapter 1: Single photon detectors
Chapter 2: Preparation of single photon states
Chapter 3: Anti-correlation at a 50/50-beam splitter cube
Chapter 4: Single photon interference.

Further details of the concept are published in (Bitzenbauer & Meyn, 2020).

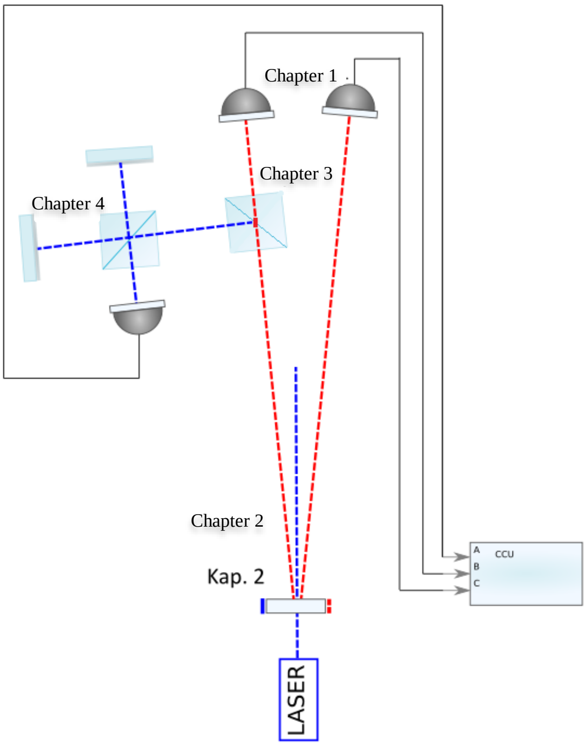

Fig. 1. Schematic experimental set-up of the experiment from the publication by Grangier et al. (1986). The individual components of the experiment are dealt with in the individual chapters of the teaching concept.

3 DESIGN OF THE STUDY

3.1 Research questions

The new curriculum was formatively evaluated during its development by means of acceptance surveys (Bitzenbauer & Meyn, 2020a). For the summative evaluation of the Erlanger concept, a mixed methods-design is used. Different qualitative and quantitative methods of empirical research are used to investigate the learning effectiveness of the concept. However, our research questions go beyond a mere learning gain: Providing a modern picture of quantum physics at the level of the upper secondary school is a central goal of the Erlanger teaching concept of quantum physics. We are therefore particularly interested in the conceptions of the quantum world that are developed by students who are introduced to quantum physics with this new curriculum. By the term *conception* we mean representations and notions that people give to phenomena or their underlying patterns (Rickheit & Sichelschmidt, 1999).

In this article, we consequently address three research questions:

1. Which conceptions about the quantum world do students have who are introduced to quantum physics with the Erlanger teaching concept?
2. Which types of learners' conceptions about the quantum world can be found?
3. Is it possible to make learners aware of the importance of quantum technologies for their everyday lives with the Erlanger concept?

3.2 Methods and participants

During the summative evaluation a total of 171 learners (12 classes of grade 11/12) were introduced to quantum physics with the Erlanger concept. The participants' prior knowledge was controlled with the help of a pre-test on declarative knowledge in quantum physics. From the results of a post-test, it was found that the students recorded significant increases in declarative knowledge of quantum physics. These (and further) findings are presented in (Bitzenbauer & Meyn, 2020b).

In order to address the above-mentioned research questions, a random sample of $N = 25$ students out of the total sample was interviewed after the intervention (15 male, 10 female). The interviews had a duration of 25 – 40 minutes and were scheduled as individual interviews. The interview guideline was prepared according to the requirements of a “good interview guideline” (Niebert & Gropengießer, 2014) including the procedure to be followed by the interviewer, as suggested by Bolderston (2012):

- keywords for a preamble in which confidentiality and consent issues are addressed with the participant,
- questions on the agenda,
- enquiry questions to help participants deepen their answers and
- a closing statement of thanks

Our guideline is the result of a multi-step development process, including a pilot interview and expert discussion, as recommended by McGrath, Palmgren & Liljedahl (2019).

The interview questions provide insights into the associations the learners have with quantum physics in a number of ways. For example, the interviewees were asked to describe what constitutes quantum physics for them, they were supposed to distinguish between quantum physics and classical physics, or they had to characterize the quantum world.

3.3 Data analysis

3.3.1 *Analysis carried out to answer research question 1*

The students' answers were evaluated on the basis of deductive and inductive categories using qualitative content analysis (Mayring, 2000). The definitions of the five categories found are presented in table 2, including anchor examples. The coding off all students' answers was carried out by independent coders using a coding manual with a high level of agreement ($\kappa = 0.84, 95\% - CI\ [0.68; 1.00]$).

In this study, we consider a student to have a certain conception if at least one statement was made during the interview that could be assigned to the associated category. In the process of coding, each category is treated equally. Subsequent occurrences of the same category in the transcript of one participant are not coded, since repetitions of the same expression or the repeated use of a similar explanation do not provide new insights into the participants' conceptions. Frequency analysis is applied to count the occurrence of a category and helps to clarify research question 1.

3.3.2 *Analysis carried out to answer research questions 2 and 3*

As we are not only interested in isolated ideas (discussed in research question 1) but also in the underlying structure of students' conceptions about the quantum world, cluster analysis was conducted in order to address research question 2. Cluster analysis is an explorative method of empirical research to identify groupings within a sample (Eshghi et al., 2011).

To conduct cluster analysis based on the qualitative data from our interview study, the categories were used as binary variables (0 = "Student did not address category during the interview", 1 = "Student did address category during the interview") because a published simulation study provides evidence that hierarchical cluster analysis and K-means perform well with dichotomous data (Henry et al., 2015). In this research article, it was found that hierarchical clustering can produce valid solutions with samples as small as $N = 20$ (ibid.).

Thus, hierarchical-agglomerative clustering methods were used in this study to determine the optimal number of clusters, namely using the Manhattan metric and Ward's fusion algorithm (Strauß & Maltitz, 2017). On the basis of the cluster solution found using a dendrogram (Backhaus et al., 2016; Denis, 2020), a partitioning K-Means cluster analysis was used to classify clusters. Interpreting cluster analysis results, we go along with the suggestions provided by Henry et al. (2015) according to which, for smaller samples (in our study $N = 25$), the solution with few clusters should be given priority over the solution with many clusters, since "in addition to taking parsimony into account, the assignment accuracy is higher with fewer clusters, but can decrease rapidly as the number of clusters increases" (ibid., p. 1014).

It is noteworthy that in this study, the cluster analysis neither leads to generalizable results, nor is it conducted with the aim to yield valid types of students' conceptions about the quantum world. Instead, clusters that are interpretable in terms of content yield preliminary groups of students with similar conceptual structures regarding the quantum world. Thus, they may function as a starting point for further investigations. In subsequent studies with larger samples and quantitative approaches, the findings of this first exploratory investigation will have to be validated[1].

A discussion of the results of our exploratory study against the background of published literature is presented in chapter 5 of this paper. This supports the approach and offers a first justification for the students' conceptions found.

Tab. 2. Categories that were used to analyze the interview data. In brackets we indicate an acronym for the categories, respectively.

Category	**Definition**	**Anchor example**
Continuous transition to ever smaller objects [ContTrans] (Wiesner, 1996)	Text passages that refer to micro-objects or the "smallest"	*"When I think of the quantum world, I imagine [...] a fairly empty space that only contains a few small [...] particles, quantum objects."*
Quantum world as a world of dualism / the model description [Dualism] (Wiesner, 1996)	Text passages that make clear that the quantum world requires a model description.	*"The quantum world is difficult to put into words, simply because we can only make it imaginable through models, whereby none of these models really applies [...]."*
Quantum world as a world of effects or facts that do not appear in the classical world [Quaneff] (Wiesner, 1996)	Relate effects or facts that exist in the quantum world but not in the classical world (e.g. quantum randomness, anticorrelation, quantization, ...).	*"[...] really the quantum randomness, that it is simply completely random and you can't say in advance [...] what will happen next, because that [...] is completely random and not like in the real world."*
Quantum world with opportunities for technology and research (new) [TechnRes]	Text passages that relate to quantum physics and its potential for technology and research, e.g. Quantum computers.	*"With [...] quantum physics and technology, we can also develop these quantum computers so that we can [...] calculate a little faster with them and [...] create a better view of all of our data."*
Quantum world as a world without concrete imaginability (new) [Unimaginable]	Text passages that refer to the fact that the quantum world and / or its elements cannot be imagined visually.	*"In the classical world [...] everything has a position and for everything you can imagine what it looks like, and in the quantum world that's just not the case, so you couldn't say what a photon really looks like [...]."*

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[1] This approach is justified by the fact that there is a lack of empirical physics education research on learning modern quantum physics. As there no research has been published on the learning processes in this field yet, explorative approaches are necessary to open up the field.

4 RESULTS

4.1 Results of qualitative content analysis

The most common category was *Quantum world as a world of effects or facts that do not appear in the classical world* [Quaneff]. 68% (17 of 25) of the respondents named aspects such as quantum randomness, anti-correlation or non-locality to define what constitutes the quantum world for them (see figure 2). It is noticeable that 48% (12 of 25) of the students described quantum objects in the sense of a replica concept and also spoke about them in that way (*Continuous transition to ever smaller objects* [ContTrans]), but that 56% (14 of 25) of the respondents also expressed the need for restrictions: One cannot imagine quantum objects as classical particles (*Quantum world as a world without concrete imaginability* [Unimaginable]). At least 24% (6 out of 25) of the learners made statements for both categories at the same time, e.g.:

> I: *"[...] What actually is quantum physics, what defines quantum physics and the quantum world for you, what would you say?"*
> B20: *"Yes, I think [...] the working with the, I say, the smallest parts that you can imagine, or that you actually can't imagine [...] so, [...] those smallest sub-components of the smallest components, so to speak"*

In 48% of the cases (12 out of 25) respondents made statements that fall into the categories [Quaneff] and [Unimaginable], and so it can be assumed that these two conceptions seem not to occur independently of one another. That means: Learners who characterize the quantum world via quantum effects are also often aware that quantum objects cannot be assigned a shape in the classical sense.

At least 28% (7 out of 25) of the respondents stated that quantum theory provides potential for technology and research. The respondents referred to quantum computers and cryptography in particular:

> I: *"[...] Then I would say we are about to start and my first question would be that you could please describe what the quantum world actually means for you."*
> B9: *"I remember quite well the introduction to the topic, that of data security and quantum computers, and that's why I believe that quantum physics will actually be our future too, that at some point we can no longer be without it. And the understanding behind it."*

Such considerations indicate the student's awareness of the importance of quantum physics for modern technologies today, and especially for the future. In order to get a more precise overview of the types of students' conceptions that arose from the introduction of the Erlanger teaching concept of quantum physics, it must be analyzed which categories apply particularly frequently synchronously with learners. This was investigated using cluster analysis.

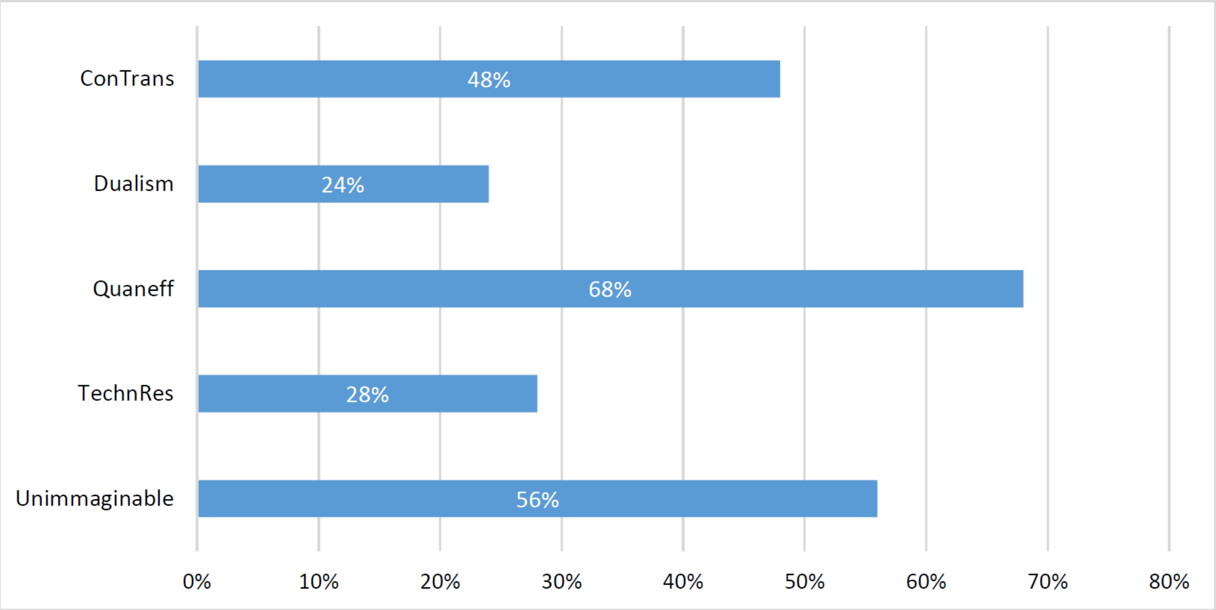

Fig. 2. Percentage of respondents making statements that fall into the respective category.

4.2 Results of cluster analysis

In a first step, the results of the coding of all student responses were subjected to a hierarchical-agglomerative cluster analysis using Manhattan metrics and Ward's fusion algorithm (3.3.2). Taken together, the dendrogram (see figure 3) and the arguments in terms of content led to a 3-cluster solution. A partitioning K-Means cluster analysis was calculated on the basis of the cluster solution found.

If one compares the statements of the respondents within the clusters with those of the total sample, striking differences between the clusters are revealed. These enable the content description of the extracted imagination types (see chapter 5).

Table 3 therefore shows which percentage of the respondents of each cluster made statements that can be assigned to the respective categories.

In figures 4-6, we also show this graphically in comparison to the distribution within the total sample, i.e. in comparison to the results from figure 2. In the next chapter, we give an interpretation of the clusters and discuss the results with previous findings from physics education research.

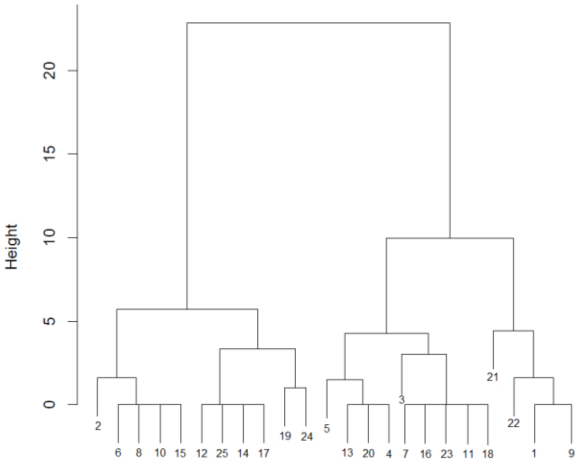

Fig. 3. Dendrogram with the three clusters.

Tab. 3. Summary of the three clusters on the students' conceptions about the quantum world and quantum physics. Numbers shown are those of learners per cluster (#Students) and the percentage (rounded) of respondents within the cluster who made statements in their responses that can be assigned to the respective categories.

Cluster	# Students	[ContTrans]	[Dualism]	[Quaneff]	[TechnRes]	[Unimaginable]
1	11	0%	19%	100%	27%	64%
2	4	50%	25%	0%	100%	25%
3	10	100%	30%	60%	0%	60%

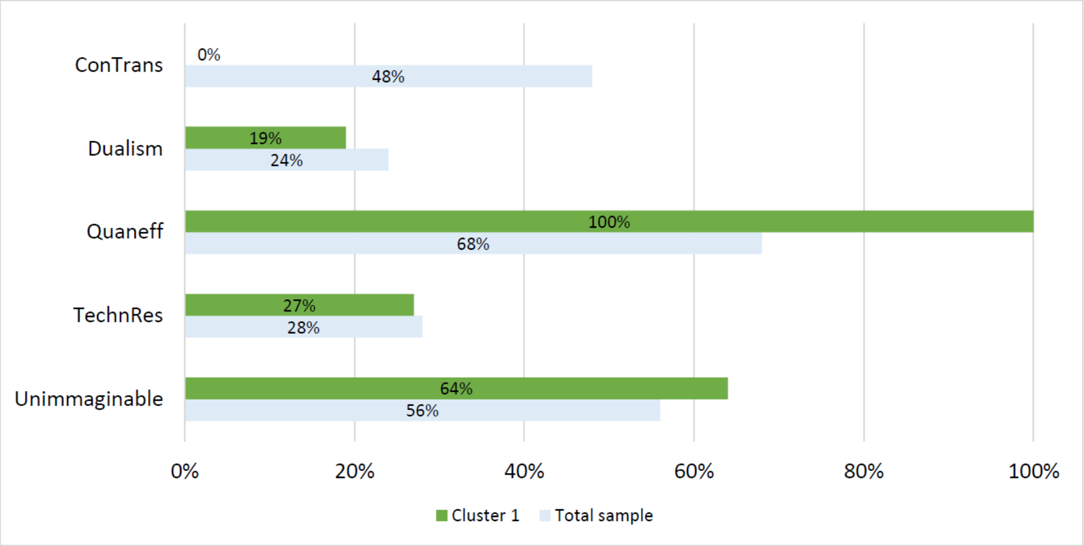

Fig. 4. Comparison of response behavior of students from cluster 1 with the total sample.

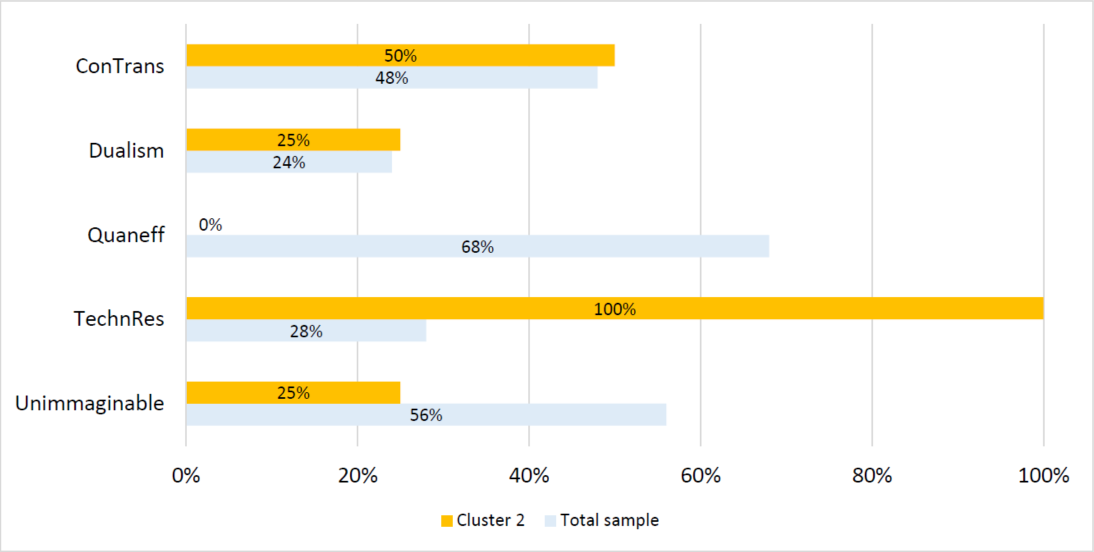

Fig. 5. Comparison of response behavior of students from cluster 2 with the total sample.

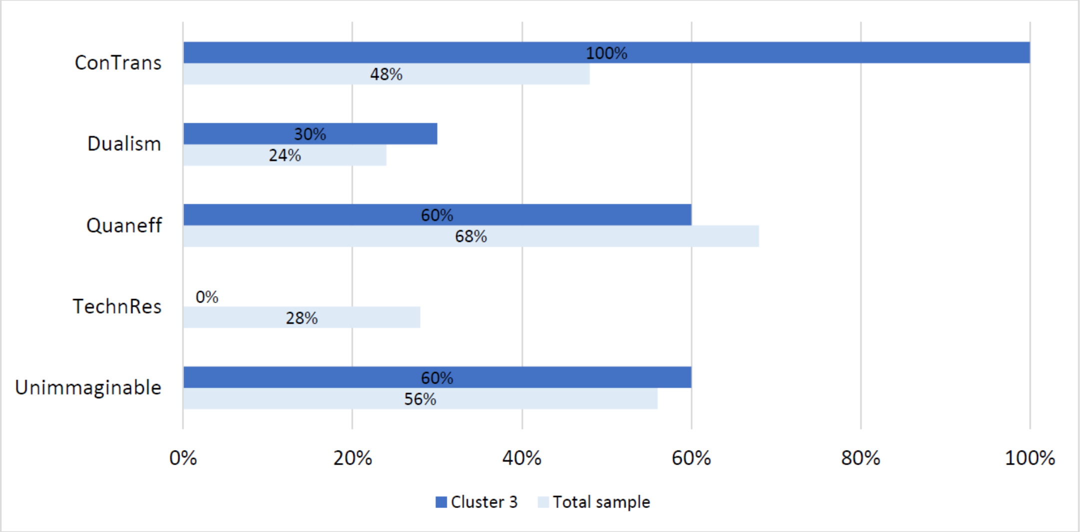

Fig. 6. Comparison of response behavior of students from cluster 3 with the total sample.

5 DISCUSSION

5.1 Research question 1

We carried out an interview study with $N = 25$ students. These were introduced to quantum physics with the Erlangen teaching concept for quantum physics (see Chapter 2) and had no prior knowledge. A goal associated with the new teaching concept was to emphasize the importance of quantum physics and its technologies. In this way, a contribution to the learning of quantum physics should be made.

Based on the interview data, we found five categories among the student responses, which can be found in Table 1. These ideas do not arise independently among the learners, as we have seen for the two concept categories [Quaneff] and [Unimaginable] and from the results of a cluster analysis.

5.2 Research question 2

Using cluster analysis, we extracted three types of student conceptions about the quantum world (chapter 4.2). In this discussion. we intend to give an interpretation of these clusters.

Cluster 1 – Primarily elaborate conception

Students in this cluster characterize the quantum world in 100% of the cases via effects or aspects that do not exist in classical physics, for example with a lack of determinism or anti-correlation. None of the learners in this cluster talks about quantum objects as “smallest particles” in the classical sense. Instead, seven of the respondents in this cluster explicitly emphasize that quantum objects cannot be compared with objects from classical physics, and that a visual illustration may therefore be allowed, but must not be confused with reality. 27% (3 out of 11) of the learners in this cluster include the importance of quantum physics for technology and research in their answers, e.g.:

> I: *"My first question to you is, why don't you just describe in principle what quantum physics is for you."*
> B2: *"For me, quantum physics cannot be described with things from our world, because you might think of things in our reality in miniature, but it's not that simple. So in our world there are laws that are practically different in quantum physics."*
> I: *"Can you describe a little more precisely what you mean when you say that you can't just make things smaller?"*
> B2: "*Yes, e.g. in our classical world every object has a place; that is not the case in the quantum world. Electrons and photons do not have a fixed location, so they are not localized and [...] you can actually only measure them with such a detector."*

In this cluster, 11 of the students are incorporated, which corresponds to 44% of the total sample. 60% (6 out of 10) of all females have such elaborate ideas about the quantum world, but only a third of males (5 out of 15).

Cluster 2 – Quantum world as the world of technology
Students in this cluster characterize the quantum world in 100% of the cases through its importance for technology and research, for example, in relation to quantum computers or quantum cryptography. None of the learners in this cluster express thoughts that specifically relate to quantum effects, but 50% make statements that speak in favour of the continuous transition to "smaller and smaller particles". Only one student in the cluster explicitly emphasizes that quantum objects cannot be compared with objects from classical physics and that a visual illustration may therefore be allowed, but must not be confused with reality. One example for a student from this cluster is B9:

> B9: *"So for me, these are just the smallest particles that still determine our whole world and our lives, including technology. So quantum particles are e.g. even electrons and nowadays without electricity you can tell that you can't do anything. Or when you think of data security and quantum computers, I already think that quantum physics will be our future [...]"*

In this cluster, 4 of the learners are incorporated, which corresponds to 16% of the total sample. 20% (2 out of 10) of the females in this cluster have such ideas about the quantum world, and 13% of the males (2 out of 15).

Cluster 3 - Quantum world as a classical world on a small scale
Students in this cluster characterize the quantum world in 100% of the cases using a clearly articulated notion of scaling. They think of quantum objects as the "smallest particles" that are "too small to be seen" and are the "components of the smallest building blocks". These associations of quantum physics to small particles indicate a misunderstanding of quantum physics, but it should be emphasized that this does not always go hand in hand with the idea of quantum objects as classical "particles". At least 60% (6 out of 10) of those surveyed in this cluster even emphasize that pictorial representations of quantum objects are not adequate. None of the learners in this cluster express thoughts that specifically relate to the importance of quantum physics for technology and research. An example of one of the students' answers is the following of B11:

> I: *"And now I would just ask you, what makes the quantum world for you."*
> B11: *"Well, it's all pretty small. [...] When I think of the quantum world, I just imagine a pretty empty space with just a few small particles, quantum objects."*
> I: *"So what makes the difference between the classical world and the quantum world for you?"*
> *B11: "[...] That we just can't really say anything because as soon as we try to read it, the property changes. The classic world is a little more robust."*

In this cluster, 10 of the test persons are incorporated, which corresponds to 40% the total sample. Only 20% (2 out of 10) of all females have such ideas about the quantum world, but at 53%, more than half of the males do (8 out of 15).

5.3 Research question 3

11 of the 25 test persons can be assigned to cluster 1, which combines the most elaborated view on the quantum world. Four more students can be sorted into cluster 2. The conceptions of these students are predominantly influenced by the importance of quantum physics for technology. Taken together, 15 of the 25 students develop conceptions about the quantum world that seem to be detached from classical ways of thinking mainly. From these results, one might deduce that introducing learners to quantum physics with the help of the Erlanger concept can successfully promote elaborate conceptions of the quantum world, and especially create an awareness of the importance of quantum technologies for the everyday life of learners today and in the future. However, in order to finally clarify this research question, more suitable instruments and quantitative study designs must be chosen, as already indicated in chapter 3.3.2.

5.4 Comparison of the results with literature on students' conceptions of the quantum world

Using data from a questionnaire survey of physics students on quantum physics, Ireson (1999) conducted a cluster analysis and was able to identify three types of students' conceptions of quantum physics. These clusters were labelled quantum thinking, intermediate thinking and mechanistic thinking. As an example of mechanistic thinking, Ireson (ibid., p. 197) specifies the students' imagination of the photon as a small, spherical entity. On the other hand, the imagination of the photon as a “'lump' of energy transferred into or out of the electromagnetic field” represents an example of quantum thinking for Ireson (ibid., p. 197). These three levels in the learners’ conceptions between classical thinking to quantum thinking are repeatedly reported in further articles, with only the naming of the three types varying (Ke et al., 2005).

The three clusters of students’ conceptions about the quantum world extracted in this article using data from an interview study fit into this scheme: Cluster 1 *“Primarily elaborate conception”* can, for example, be well associated with Ireson's (1999) cluster *quantum thinking* in terms of content: While students in this cluster characterize the quantum world by quantum effects [Quaneff] (100%, 11 out of 11) or the lack of a visual representation of quantum objects (64%, 7 out of 11, category [Unimaginable]), scaling conceptions or particle notions are not expressed (0%, 0 out of 11, category [ContTrans]) by these students.

Students of cluster 2 “*Quantum world as the world of technology”* may be associated with the *intermediate thinking* in the regime of Ireson (1999). While all four students in this cluster describe quantum physics in terms of its potential for technology and research (category [TechnRes]), particle conceptions are not entirely absent here (50%, 2 out of 4, category [ContTrans]). Of course, a larger number of participants and different instruments would be necessary to validate this type of imagination (chapters 3.3.2 and 5.5).

Cluster 3 *“Quantum world as a classical world on a small scale”* can, consequently, be associated with Ireson's (1999) cluster mechanistic thinking: all of the 10 students in this cluster remain in classical imaginations, e.g. thinking of quantum objects as the "smallest particles" (100%, 10 out of 10, category [ContTrans]). Thus, a successful conceptual change towards quantum thinking cannot be observed in the context of our interview study for students in this cluster.

Furthermore, the results of Wiesner’s (1996) interview study with $N = 27$ students from secondary school into differences between classical objects and quantum objects can directly be compared with the types of conceptions reported in this article, as for the category system used in our interview study, we resorted to categories by Wiesner (1996). There are certain similarities between the results reported then and the results of the interview study reported here but also differences: If one summarizes statements on energy quantization, Heisenberg’s indeterminacy relation, the property *location* of quantum objects, as well as effects that only occur in quantum physics, as the category quantum effects, 49% of Wiesner’s respondents fall into this category, as cited in Müller (2003, p. 22) - this percentage is higher in the investigation reported here (68 %). In addition, in this study, the category *Quantum world with opportunities for technology and research* [TechnRes] is one that was not documented in the study by Wiesner (1996), but with regard to which 28% of the respondents make statements here.

In both studies, around a quarter of the respondents describe dualism, i.e. the need for model descriptions, as the central difference between classical physics and quantum physics: 26% of the respondents in Wiesner’s study, as cited in Müller (2003, p. 22), and 24% of the participants in the study presented in this article.

In summary, the results of the cluster analysis reported in this article fit well with previous findings from physics education research – this contributes to the justification of the results presented in this study. Although the clusters found can still only be described as preliminary types of students' conceptions about the quantum world, the results indicate that fostering quantum thinking could be promoted by introducing learners to quantum physics with the Erlangen teaching concept (cf. chapters 5.2 and 5.3). However, in order to draw more valid and reliable conclusions of this kind, certain limitations must be tackled in subsequent studies.

5.5 Limitations

To assess the results reported in this paper, the following note is essential: Each of the five categories presented in table 1 was coded dichotomously for each student. If several statements were made that are suitable for assignment to the same evaluation category, they were still only coded once, since repetitions of the same expression or the repeated use of a similar explanation do not provide new insights into the participants’ conceptions (chapter 3.3.1). For each respondent, it can only be determined whether or not statements were made that fall into the corresponding categories. If the respondent did not make any statements that could be assigned to category X, it must not be concluded from this that the respondent does not have the idea X – he/she simply did not express it. To minimize the likelihood of learners’ conceptions remaining unarticulated during the interview, we used the procedure of internal triangulation: we referred to the same aspects at different points during the interview, increasing the chance that learners would express all their ideas about the topic during the interview. This is an accepted procedure to ensure validity in interview studies (Niebert & Gropengießer, 2014). A solution that could better differentiate between the various manifestations of several students’ conceptions could lie in using a questionnaire with different items concerning the quantum world, where participants can indicate their agreement or disagreement on a rating scale, as it was done in various studies on similar topics (Ireson, 1999; Ubben & Heusler, 2019). However, in order to develop suitable items for such a questionnaire, a deeper insight into students’ conceptions on the topic is required. Thus, we argue that while this must be desirable for subsequent investigations, an exploratory approach, as presented in this article is suitable to open up the field.

Taking into account all the above-mentioned points, the types of students’ conceptions extracted by cluster analysis in this article are not to be understood as fixed, strict types, but rather as preliminary imagination patterns. Of course, this applies not least because the sample size of $N = 25$ does not allow generalized conclusions.

6 CONCLUSION

In this article, we presented the results of an interview study. We surveyed conceptions about the quantum world of 25 students from 11th and 12th grade of German secondary schools who were introduced into quantum physics with the Erlanger teaching concept. The presented results provide implications for both classroom practice and future research. For classroom practice, the Erlanger teaching concept serves as a proposal to bridge the gap between quantum physics and the everyday life of the learners. In addition, the results of the interview study presented in this paper make a contribution to the empirical research on students’ conceptions about quantum physics. Not only do we find individual, independent conceptions of learners, but we also show that there are dependencies between them so that we are able to extract types of conceptions. The extraction of such types of student conceptions for various further concepts of quantum physics will be part of future research and could contribute to our understanding of learning processes in quantum physics.

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