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Research Article

Pre-service physics teachers' use of photon concept in the context of single-photon double-slit experiment

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ABSTRACT

Research in physics education has revealed that students often have incomplete and incoherent ways to use the concept of photon. Most researchers in science education recommend photons to be taken in a realistic sense as existing entities of quantum objects. Furthermore, in science education literature it is often claimed that realistic stance to photons also is preferred by physicists. Taken that photons in quantum theory of light invariably refer to quantized degrees of the freedom of an electromagnetic field it is questionable how one should introduce photons as entities without inadvertently supporting naïve particle-realism about photons, a well-known situation in introductory teaching of quantum theory of light. Fewer researchers suggest that photons should be understood as photon states, quantized degrees of freedom of electromagnetic field, as in contemporary quantum optics and quantum theory of light. Here, by using a questionnaire (a Likert-scale survey), we explore pre-service physics teachers' preferences to use expressions that can be associated with either quanton or photon state views about photons in context of single-photon double-slit experiment. The questionnaire is administered in two stages (in the beginning and after a teaching sequence) during a pre-service physics teachers' course addressing quantum optics and technology. Based on the analysis of the responses, we find that at the beginning of the course, the responses are scattered but in the final survey, clusters corresponding to use of photon state-based expressions become more consistent.

Keywords: photon, quantum state, double-slit experiment, pre-service teachers

INTRODUCTION

Physics education research has placed a great deal of attention on learning the photon concept and on the role of wave-particle in it (Ayene et al., 2011, 2018; Bouchée et al., 2018; Bungum et al., 2015; Cheong & Song, 2014; Didic et al., 2014; Greca & Freire, 2003; Henriksen et al., 2018; Krijtenburg-Lewerissa et al., 2017, 2019). The interest towards photon concept is obviously partly due to increasing importance of quantum optics and technology in modern society (Greinert et al., 2023), but also to centrality of photons in understanding quantum nature of light. The reasons to pay attention on wave-particle duality (WPD) owe to the assumption that WPD is central for learning quantum physics, as discussed in several studies (Ayene et al., 2018; Bouchée et al., 2022; Cheong & Song, 2014; Didic et al., 2014; Henriksen et al., 2018; Lautesse et al., 2015) whose main findings are not reiterated here.

Here, we take a viewpoint, which does not take WPD necessarily so central as assumed in most science education studies. Instead, we take photon as a concept that describes quantized degrees of electromagnetic field, aligning with how photon is understood in modern quantum optics and quantum theory of light (see, e.g., Gerry & Knight, 2004). No more (ontological or entity) realism that that is associated with photon concept here. However, we know from previous studies that students as well as pre-service teachers (probably in-service teachers too) tend to have strongly realistic views about photons as particle-like entities but with new non-classical properties. Therefore, this study addresses the question: how consistently pre-service physics teachers choose between expressions that emphasize particle-like nature considering photons as kind of quanton-like entities (Bunge, 2003) as new quantum entities with non-classical features, or rather view photons as photon states, with real existence insofar as the quantized degrees of freedom are considered real. Both ways to consider photons are feasible, but commitment either to a quanton-picture or a photon state-picture entitles different kinds of statements about behavior of photons in different experiments. Learning to use correct and justified expressions as part of inferences and in discussing experiments where concepts of photon appear is an important part of learning how photon concepts are used in modern quantum theory of light and quantum optics. Obviously, pre-service physics teachers will be in key role in communicate that understanding to new generations of citizens as well as future "quantum workforce" (Greinert et al., 2023).

The viewpoint adopted here does not put emphasis on ontological questions about photon (i.e., its existence as a real entity). Instead, we consider photon as a concept describing quantized degrees of freedom of electromagnetic field, thus having a real existence only to a degree such quantized degrees of freedom (i.e., photon states) have a real existence. For all pragmatic uses this is enough, and no deeper metaphysical inferences are needed. Therefore, we will not discuss WPD except in its instrumental (operationalized) role as quantitative notion of distinguishability of photon states, operationalized through quantum information theoretical approach. Consequently, we assume that regarding the learning of photon concept, it is better to focus on pragmatic questions on how normative and correct use of concept photon is learned, how pre-service physics teachers recognize different possibilities and commitments behind them as well as what statements they are entitled to make by using the differently grounded concept of photon. The different groundings of interest here are quanton-like view, based on sophisticated enough realism (Bunge, 2003; Levy-Leblond, 1988) and quantum states of quantized light (Greca & Freire, 2003) (in what follows we call this photon state). The latter view agrees with contemporary mainstream introductions to quantum theory of light in quantum optics (Gerry & Knight, 2004).

Following the above outlined viewpoint we have designed a questionnaire which attempts to provide information on how coherently and consistently pre-service physics teachers use the concept of photon in context of well-known double-slit experiments (DSEs) for dim light. The empirical study reported in this article investigates pre-service physics teachers' preferences to use expressions related to either photon as quantum particle (quanton) or as photon state in context of DSE. Some additional statements are related to WPD. The questionnaire uses a Likert-scale for expressing agreement-disagreement to statements about photon as quantum particle and photon as photon state. In the analysis, we pay attention on the coherence and consistency of the use of photon as quantum particle or photon state when focus shifts from slit to detection system. The study was conducted as a part of a new quantum physics course mandatory to pre-service physics teachers, with a purpose to make pre-service physics teachers acquainted with basic concepts of quantum optics, e.g., superposition, entanglement, photon, and the probabilistic nature of quantum physics.

PHOTONS IN SCIENCE EDUCATION

Newtonian mechanics introduced to students in the upper secondary school level makes students familiar with classical particles as idealized object-like entities that have mass and can have well-defined location, speed and thus, trajectory. In other introductory courses, students become familiar with concepts of waves and fields, which are introduced as time and space dependent, sometimes propagating but extended and non-localized displacements of certain quantities like surface position in waves or fluids, or the strength of electric or magnetic field in electricity and magnetism. Particles and waves are learned as two classical entities that are exclusive; no single classical entity or object can have both characteristics of particle and wave.

Next students are introduced to the concept of photon–a light particle with no mass, moving at the speed of light and with addition of wave-like properties in certain situations (double-slit). Also, introducing photon as quantized energy packet–a light quanta–on interaction. Usually working within the frame of the classical electromagnetic field.

When students encounter the concept of photon in their first introductory courses, the particle- and wave-like characteristics become often associated as characteristics of photons, often condensed in the notion of WPD. In science education, the WPD of photons is often taken to mean that photon behaves as or shows properties of particles and waves. However, these characteristics are never present in the same experiment (aligning rather well with the historical notion of WPD). Both notions are meant to signal difference between photons and classical particles and waves (see, e.g., Bouchée et al., 2022; Cheong & Song, 2014; Didic et al., 2014; Henriksen et al., 2018; Lautesse et al., 2015).

From the modern perspective, however, the historical notion of WPD is obsolete (for detailed discussions, see Hentschel, 2018). Instead, photon should be seen as a concept, which is related to quantized degrees of freedom of electromagnetic field. In the most basic form, photon is taken as concept that refers to number of basic quantized excitations of the electromagnetic field, a quantum state described by single quantum. In the language of mathematical theory, to eigenstates of number-operator, i.e., Fock-states associated with eigenvalue one (Gerry & Knight, 2004; Hentschel, 2018; Loudon, 2000). Such single photon states, under detection with, for example, photomultiplier counters, behave particle-like fashion; measurement events being countable and separated single different localized events not affecting each other. However, it is common also, to use photon to address more complex states, so called "squeezed states" or wave-packets, which can be treated as spatially localized states, but still, under detection, behaving like single photon (Loudon, 2000; Lounis & Orrit, 2005). These squeezed states allow a description of how photons can exhibit both wave-like properties, such as interference, and particle-like properties, such as discrete interactions, in different experiments. However, both ways to use photon concept can be and are in practice called single photon states (Loudon, 2000; Lounis & Orrit, 2015), (we refer to photon state as degrees of freedom of electromagnetic field).

Regarding particle-like behavior of photons, such behavior emerges from the fact that photon can be observed only once like particles, one event of observation not interfering or correlating with other events. When discussing the time evolution of squeezed states, it is meaningful to refer to its propagation, passage, entering, and leaving—much like how particle motion is addressed. Thus, this results a need to define the meaning of "particle like" in a new way. This way to understand photon is essentially captured by the notion of quanton (Bunge, 2003; Levy-Leblond, 1998), to be used in what follows.

Regarding wave-like behavior, in many quantum optics experiments (Gerry & Knight, 2004; Loudon, 2000), single photon states may have different phases. The phase difference shows up as coherence between probability of observability or distinguishability of the state (Kauark-Leite, 2017; Wootters & Zurek, 1979; Yoon & Cho, 2021). This phase-factor dependence of photon-state can be associated with the interference-like behavior of single photons, interpreted now in terms of different probability amplitudes associated with possibility of different photons states. Consequently, when repeated measurements are accumulated interference pattern-like statistical distribution of accumulated counts emerge when phase difference is varied. The interference-like behavior although in its mathematical description sharing much similarity with interference of classical fields, is a phenomenon in many ways different from classical interference of continuous fields, where real, directly measurable field amplitudes show interference.

To reduce confusion between classical and quantum view, we chose, for teaching purposes, a conceptual level where photon is comprehended as an electromagnetic field's quantized degree of freedom, a photon state, along the lines outlined above and thus, omitting the notion of WPD. This provides us a grounding where we can present and talk about fundamental concepts of quantum physics, such as superposition, entanglement, probability waves, which also align well with modern quantum optics. **Figure 1** illustrates this conceptual diversity: how concept of photon develops from classical particle view to quantum view. To access quantum nature of reality within context of quantum optics, it is necessary to understand the concept of photon. Therefore, it is clear that photon serves as a central concept that students must grasp to fully understand the quantum nature of reality within the context of quantum optics.

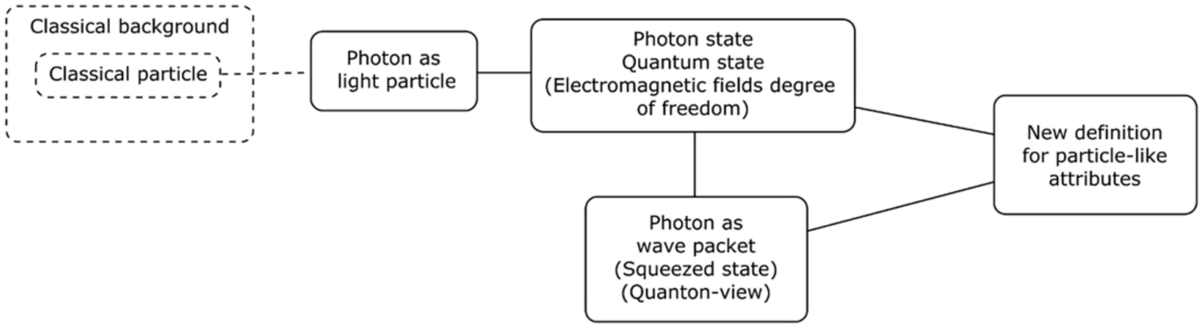

Figure 1. Schematic representation summarizing the topics and connections discussed in text in more detail (dotted line indicates expected background knowledge of students) (Source: Authors' own elaboration)

METHODS AND MATERIALS

This study focuses on how pre-service physics teachers prefer to choose expressions related to different ways to use photon concept. Do they lean towards choosing "particle-like" descriptions, viewing photons as quantons, where terms like propagation, entry, and passage are used to describe the position of photon, using the expression "particle-like" in a new way? Or do they prefer expressions where the photon is seen as a photon state of quantized light (the electromagnetic field), where different expressions like creation, transformation, and merging are more appropriate? These questions were approached by using a Likert-scale questionnaire, where questions were formed against the backdrop as outlined in the previous section.

The Questionnaire

The questionnaire consists of 24 statements, all related to well-known single-photon DSE. Pre-service physics teachers were told that in the experiment, single photon states were created using dim monochromatic and coherent light and observed as "clicks" with an array of photomultiplier tubes (i.e., electron multiplying EMCCD camera). First, counting statics was checked to confirm that mostly single, well time-separated clicks are observed (i.e., sub-Poissonian counting statistics). Second, spatial distribution of counting events is obtained, resulting to probability density distribution that is similar to interference pattern. The description and interpretation of the outcome of the experiment can be done equally well by taking photons as quantons (as outlined later), or as photon states used to describe quantized degrees of electromagnetic field. Both choices are possible when used consistently.

The questionnaire statements were designed so that each item suggests a choice to use expression understood as either

(1) quantons or using expression that are either space-time -like speaking about coming, entering, passing, propagation and direction of movement or

(2) photon state or using expressions referring to states existing, being created, or transformed or localized, or wordings emphasizing stochastic or probabilistic nature.

In the beginning of the questionnaire, a schematic picture of the experimental set up was given along with short descriptions of what is meant by photons as quantons and as photon states. Statements are made about events and observations in three separate parts of the experimental set up:

(1) grating (slits),

(2) region between grating and detector (EMCCD camera), and

(3) detector (EMCC camera). In the questionnaire, the statements were organized under thematic contexts regarding the experiment and its interpretation: predictability (statements number 1–9), indistinguishability (11–14), self-interference (15–16), single hits and interference pattern (17–20).

For benchmarking the role of WPD, statements related to WPD (21–24) were also included. Participants were asked to evaluate their agreement with the statements by using a Likert-scale from one to five. Where values stance for: One (strongly disagree), two (somewhat disagree), three (undecidedness), four (somewhat agree) and five (strongly agree).

The statements in the questionnaire (see **Appendix A**) are designed to challenge the respondents to consider carefully how they can use concepts related to photon in a coherent and normative way. When probing pre-service physics teachers coherent use of concepts in normative way with a such pre- post-questionnaire, special attention to the formulation of the questions is necessary. The questions should have enough linguistic complexity so that answers are not obvious but enough focusing and thought is needed to make the choice. The answering pattern is then expected to dominantly show preference for using either formulations based on quanton-like expression or expression based on use photon state.

Some of the statements, although based on either photon or photon state framing, use expression familiar from textbooks, but which do not have unambiguous meaning and are rather kind of metaphors. Among these are notions like "photons interfere with itself" and "photons pass through both slits" (but not phrases like "photons cannot be splitted"). In each statement, however, photon and photon state are key words. The purpose of these statements is to check how consistently pre-service physics teachers commit either to a quanton or photon state picture despite the metaphorical non-explanatory notions.

Sample and Data Collection

In this study, the data is the answers on a Likert-scale questionnaire consisting of 24 statements about the photons in the context of the DSE, either from a quanton or photon state viewpoint. The data was collected in a pre-post setting from a physics teacher preparation physics course on contemporary quantum optics and technology. The participants answered the questionnaire in the beginning of the teaching (pre-survey) and after the teaching sequence that focused on photon states (post-survey). The course was for seven weeks, intermediate level and five ECTS. The course focused on entangled photon states, distinguishability of photon states in interferometric experiments and different DSEs. The participants of the study (N = 23) were pre-service physics teachers who were in their 2nd or 3rd year in their BSc level studies, and they had already passed the basic level physics studies. More detailed description of the contents of the course is provided in **Appendix B** (see also Koponen et al., 2025).

AI & Ethical Declaration

Open AI was minorly used for language editing but before approving the AI suggestions, they were critically reviewed by the authors. Research was conducted in accordance with the ethical guidelines of the University of Helsinki fulfilling the ethical guidelines set by Finnish National Board on Research Integrity. Participation in the research was voluntary, and research consent was obtained from all participants. Participants were adequately informed about the research, and the anonymity of the participants was protected during the research.

Correlation Analysis

The responses to the statements in the questionnaire are in Likert-scale from one to five. Where values stance for: one (strongly disagree), two (somewhat disagree), three (undecidedness), four (somewhat agree) and five (strongly agree). However, because it turned out difficult with the available information (e.g., no interviews after questionnaire were conducted) to clarify difference between choice 1 and choice 2 as well as between choice 4 and choice 5, we reduced the information of choices contained in Likert-values to simpler dichotomous variable $X \in \{-1, +1\}$ with value +1 (agree) corresponding choice 4 and choice 5 and value –1 (disagree) choice 1 and choice 2, while choice 3 (undecidedness) was ignored. The objective of the research conducted is to focus on whether the respondents prefer one view of photon concept over other (realistic vs. quantum) so in the research we are primarily interested in answers related to the dichotomic situation. We acknowledge that neutral responses to Likert scale questionnaire provide information, but regarding our research it is not relevant.

The correlations in answering patterns as represented by the dichotomous variable X are explored in two ways. In both cases, however, the correlation is based Kendall rank (tau) correlation coefficient (Abdi, 2007). The Kendall rank correlation coefficient is chosen because it is a nonparametric correlation test, not assuming normal distribution of data. To check the statistical significance the p-values for Kendall rank coefficients are used (Abdi, 2007) with criteria $p \leq 0.05$ for statistically significant results.

First Kendall-rank correlation coefficients coefficient κ_{AB} refers correlations between values X and X' corresponding to responses in two different statement A and statement B, respectively, in the sample of all N = 23 pre-service physics teachers. Correlation coefficient κ_{AB} is used to check if there is an overall correlation between responses to items A and B within the whole sample. In large statistical sample κ_{AB} might provide important information of the statistical generalizations but not for a sample of size N = 23 this is not very likely due to expected large variations of response patterns within the sample.

Second Kendall-rank correlation coefficient κ_{PQ} refers to pairwise correlations between answering patterns $\boldsymbol{A}(P) = (X_1, X_2, \dots, X_M)$ and $\boldsymbol{A}(Q) = (X_1', X_2', \dots, X_M')$ for a pair of student P and student Q. The coefficient κ_{PQ} is referred as pairwise (student-to-student) response pattern correlation coefficient because it reveals how close is the match between answering patterns of students. Of course, high values of κ_{PQ} are now of most interest, indicating high similarity between choices made by student P and student Q. Even more interesting are triads (transitive 3-clusters) of high similarity choices κ_{PQ}, κ_{QR} and κ_{RP} of students P, Q, and R. Such triads are basic units in forming consensus clusters of choices, as well as allowing communication in a smallest unit where groupwise consensus can be expected (see, e.g., Koponen & Nousiainen, 2018; Turkkila & Lommi, 2020 and references therein).

Similarity Clusters of Response Patterns

The similarity comparisons of answering patterns between student A and student B are based on Kendall rank correlation coefficients κ_{PQ} between their response patterns. In that, we pay attention on triadic (transitive) clusters, where three students P, Q, and R have response patterns similar to each other. Triads, where all three students have similar enough response patterns, form the backbone of all other more complexly related patterns, which can be composed of triadic ones (Koponen & Nousiainen, 2018; Turkkila & Lommi, 2020). Therefore, finding triadic clusters is enough to reveal the important correlations going beyond pairwise correlations. In what follows, we pay attention only on cases, where all correlations exceed the threshold value 0.42 and have a p-value no larger than 0.05. This leaves only the most important and statistically (enough) significant triadic cluster for further analysis.

The triadic clusters of elementary response patterns as they are extracted from pairwise comparisons of complete answering patterns is the final analysis. It is important to note that the extraction of patterns is done stepwise without averaging over the patterns but instead based on clustering of similar answering patterns. Such triadic clusters provide a complementary picture of the correlation in comparison to traditional correlation analysis. In summary, the analysis here is a census method to find the basic elementary patterns that are responsible for the similarities.

RESULTS

The responses to pre- and post-survey are analyzed to find the relevant answering patterns and to conclude if desired development in coherent use of photon concept has taken place during the course. In **Figure 2**, an overview of the answer distribution in pre- and post-survey is shown. Experts' answer pattern is shown with dark shade in case of answers "agree" (+1) and with light shade for "disagree" (–1). See previous sections for a more detailed description. Values are given as relative frequencies.

When comparing the results from pre- and post-survey, we can see a positive trend that the answers are getting more aligned with the expert's view in the post-survey. The change is, however, subtle and scattered across thematically different questions. The results indicate that participants have in the post-survey slightly more answering patterns similar to expert pattern than in the pre-survey. However, due to much variation in the date, the changes when averaged over the total sample may mask the few important cases. Therefore, in what follows, we take the survey answers under more detailed inspection and examine the pair correlations, form triads, and clusters from pre- and post- survey answers.

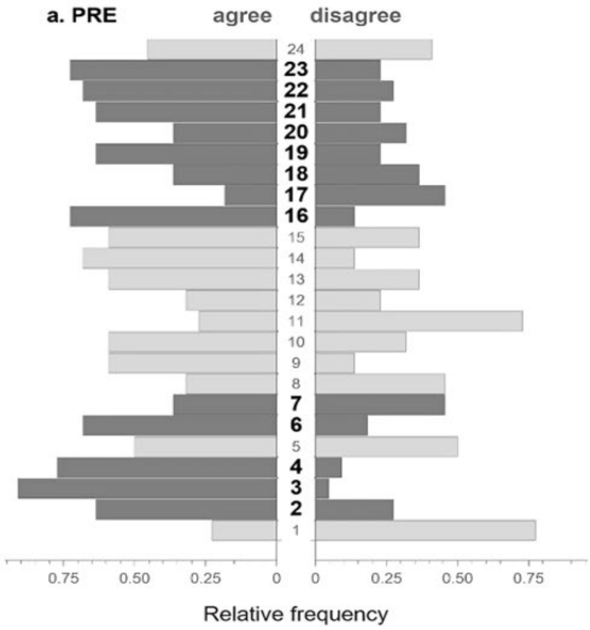

Figure 2. The answer frequencies in pre- and post-survey (columns on left represent the relative number of agrees with statements and columns on right represent the relative number of disagrees & for comparisons, experts answer pattern is indicated with darker shade [agree] and lighter shade [disagree]) (Source: Authors' own elaboration)

Response Pattern Correlations

The pairwise correlations for were calculated for both pre- and post-survey answers for complete response patterns $\boldsymbol{A}(P)$ and $\boldsymbol{A}(Q)$ of student P and student Q. For benchmarking, correlation or each student's answering pattern with expert response pattern was also calculated, to help such comparison. All triples of students P, Q, and R, which have positive correlations κ_{PQ}, κ_{QR} and κ_{RP} at least 0.42 (and a p-value ≤ 0.05) were counted as triadic (transitive) clusters, where students' answering patterns are similar enough to allow significant overlap of agreement about most statements. It should be noted, that in both cases of high correlations between "agree" and "disagree" answers correlations are of interest, a high correlation in both groups signaling a mutual coherence of preferences about appropriate statements. A threshold value 0.42 leaves us with 11 clusters in pre- and 23 clusters in post-cases. It turned out that 57% of response-patterns in pre-survey and 48% in post-survey cannot be classified in any triadic (transitive) cluster and thus, are likely to contribute to randomly distributed answering patterns. Nevertheless, some positive and statistically significant pairwise correlations persist.

The response patterns corresponding to triadic cluster for pre- and post-surveys are shown in part a and part b in **Figure 3** for patterns in pre- and post-surveys, respectively. The "agree" answers are shown in red while "disagree" answers are in blue. A network of clusters of all positive correlations exceeding the threshold are shown as a network in part c and part d in **Figure 3** for pre- and post-surveys, respectively. Each circle corresponds to a participant and O represents expert. Networks are shown in form (spring embedding), where closeness of circles is related to the strength of the correlations. The network illustration highlights that there are more clusters in the post-survey (23) than in pre-survey (11), the network is more connected and converged near expert dot (O).

From the more detailed cluster analysis, it is evident that the pre-test responses are significantly more scattered (fewer clusters) than post-test. This result is consistent with the examination of frequencies (see **Figure 2**). We can note that the expert answering pattern takes part in only two clusters in the pre-survey (see part c in **Figure 3**) but in five clusters (part d in **Figure 3**) in the post-survey. In addition, the answering patterns of pre-service physics teachers, which belong to same clusters as expert pattern, are also parts of many other clusters. This is seen dense community of triadic clusters in part d in **Figure 3**. The interpretation is obvious; in post-survey triadic cluster of similar answering patterns have gained more resemblance to expert answering pattern.

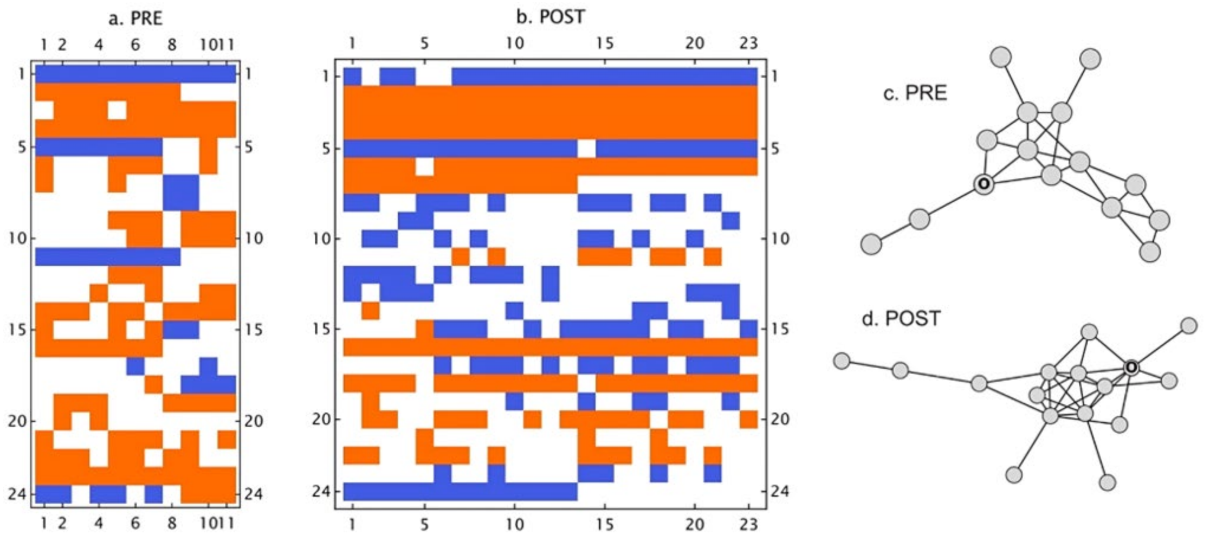

Figure 3. The response patterns **A** of 23 responses and the expert answer (vertical scale) corresponding to all triadic clusters (horizontal scale) of positive correlations $\kappa_{PQ} \geq 0.42$ in pre- (a) and post-surveys (b) (the correlation patterns showing the triads for pre- and post-surveys are shown [c] and [d], respectively & agree-responses are shown in red while disagree-responses are shown in blue) (Source: Authors' own elaboration)

A closer inspection to cluster formation (part a and part b in **Figure 3**) reveals that in both pre- and post-answering patterns, the statements 2, 3, 4, and 16 are agreed nearly unanimously as well as statements 1 and 5 are disagreed. These patterns are also found in nearly all clusters (shared patterns in pre- and post-survey, remaining intact). To slightly lesser unanimity (in a slightly lesser number of clusters) was found in responses to statements 6, 20, 21, and 22 (agreed) and 24 (disagreed). The thematical contexts where agreement and disagreement were found, is discussed in what follows. Overall, statements related to predictability in simple experimental setups with keywords available, were found to be rather easy. Scattering of responses (low consensus) of some statements could be related to formulation statement: Complexity of described situation or complexity of wording of the statement. Also, less prominent keywords might have made the choosing between different photon views more difficult.

From **Figure 3** (part a and part b) we can see a change: there are notable differences between the answering patterns in the pre and post survey. The post-survey answering patterns form clusters where certain answer appears as agreed or disagreed quite often, but similar clusters appear not in the pre-survey. These answers are important in differentiating the post- from pre-survey and thus, indicating what kinds of changes teaching intervention has caused. Statements agreed exclusively in post survey with over 50% unanimous clusters are 6, 7, 18, 20, and under 50% unanimity, but still showing positive trend, is question 11. Statements disagreed exclusively in post survey with over 50% unanimous clusters are 8, 15, 17, 24, and under 50% unanimity, but still showing positive trend, are questions 10, 12, 13, and 23. There are few answers, which are often agreed in pre-survey and disagreed in post-survey, and the other way around. In these answers, the common choices are reversed in similarity. Agreed in pre and disagreed in post with over 50% unanimous clusters is question 15 and with lesser unanimity, but clear trend, are question 10, 12, 13, 19, and 23. The other way around question disagreed in pre and agreed in post with over 50% unanimous clusters is question 18 and with lesser unanimity, but clear trend, are question 11 and question 13.

The response pattern correlation and triadic census reveals more details of coherent choices, related to coherent use of photon concept, either from viewpoint of quanton or photon state viewpoint. Probing the consensus of triads between each question in the post-survey we divided them into three groups. First group includes questions with over 85% triad consensus, meaning over 85% of the triads have same answer to a question, correlating to high unanimity (reasons behind answers analyzed in more detail in **Table 1**). Second group includes questions between 50–85% triad consensus correlating to moderate unanimity (**Table 2**). Third group includes questions with less than 50% consensus correlating to low or no unanimity (see **Table 3**). It is to be reminded that forming triad answer requires cohesive answers to the question from all three members of triad.

Table 1. 85% consensus of triads analyzed by their thematic context

Statement	Thematic context	Analysis of the situation
1, 2, 3, 4, 5, & 6	Predictability	• Simple experimental setup, which is easy to perceive, keywords easily spotted.
16	Self-interference	• Connections between adequate concepts, superposition mentioned, keywords available.
18	Single hits and interference pattern	• Photon state localization connected to collapse and particle-like distribution. • S18 answers are contradictory S17 and S19, collapse is not realized resulting in thought of interference-like pattern.

Table 2. 50–85% consensus of triads analyzed by their thematic context (statements marked with asterisk [*] had consensus within the triad, but the answer differentiated from expert's view)

Statement	Thematic context	Analysis of the situation
7 & 8	Predictability	• Movement of slit R1, more complexity in the experimental setup, keywords not easily visible. The formulation of the statement is more complex.
15	Self-interference	• Superposition not mentioned, mix of classical and photon state keywords.
20	Single hits and interference pattern	• Photon state localization linked to collapse linked to particle like distribution. • S20 answers are contradictory S17 and S19, collapse is not realized resulting in thought of interference-like pattern.
22 & 24	WPD	• Interference pattern linked to wavelike behavior.
17*	Single hits and interference pattern	• Particle distribution considered random and hard to predict. Possible conception that without interference pattern there is no pattern at all. The formulation of the statement is more complex.

Table 3. Less than 50% consensus of triads analyzed by their thematic context (statements marked with asterisk [*] had consensus within the triad, but the answer differentiated from expert's view)

Statement	Thematic context	Analysis of the situation
9 & 10	Predictability	• Complex situation due to movement of double-slit R2, harder to perceive the experimental setup, keywords not easily visible.
11, 12, 13, & 14	Indivisibility	• Complex situations, understanding relations between multiple physical concepts, e.g., absorption, scattering, momentum, and relating photon or photon state with them.
21 & 23*	WPD	• Single detections hard to link to particle like behavior.
19*	Single hits and interference pattern	• Particle distribution hard to predict or too random, possible conception that without interference pattern there is no pattern at all. Complex formulation of the statement.

Probing the triad consensus related to the questions difficulty we can clearly see in **Table1**, **Table 2**, and **Table 3**, that describing more complex situation in the question results in a less consensus correlating to difficulty in the reasoning. For example, in topic of predictability we can see how basics were understood quite well with high unanimity between triads but probing in deeper understanding by making the situation more complex, firstly including movement of slit R1 and secondly movement of dual slit R2, we see major drop in the consensus.

Interestingly topic of self-interference was high in unanimity when superposition was mentioned but less unanimity without mentioning superposition in the question. Pre-service physics teachers might be connecting superposition to a "way" or "explanation" for self-interference. Topic of single-hits and interference pattern were highly unanimous when connecting photon state to interference pattern but declining when introducing situations with particle like distribution. Similar to superposition, linking the idea of interference pattern to photon state; particle distribution becomes too hard to predict or random, or possibility that when there is no mentioning of "interference pattern" pre-service physics teachers think that there is no pattern at all. Likewise statements about WPD there is inclining of unanimity when describing attributes (wavelike) with interference pattern compared to single detections (particle like) resulting in particle distribution.

Statements marked with an asterisk indicate that the triad consensus contradicted the expert's view. For statement 17 and statement 19, the issue may lie in the overly complex wording, making the statements difficult to interpret and requiring clarification. Regarding statement 23 the challenge might be understanding the meaning behind "particle-like".

Table 4. Expert-aligned responses from all post-survey answers (yellow marked triad consensus over 85%, light yellow 50–85%, and white below 50% & the statements marked asterisk [*], triad consensus differed from expert's view)

Statement	POST RIGHT	Statement	POST RIGHT	Statement	POST RIGHT	Statement	POST RIGHT
1	73%	7	59%	13	55%	19*	41%
2	77%	8	77%	14	55%	20	55%
3	91%	9	64%	15	73%	21	77%
4	86%	10	68%	16	77%	22	68%
5	77%	11	50%	17*	27%	23*	59%
6	91%	12	64%	18	59%	24	73%

Table 5. Expert-aligned responses from all post-survey answers (**bold** numbers relate to questions where whole groups answering pattern differs from triad consensus)

Expert aligned answers	Statement number
85% or more	3, 4, & 6
70–85%	1, 2, 5, 8, 15, 16, **21**, & 24
60–70%	9, 10, 12, & 22
50–60%	7, 11, 13, 14, **18**, 20, & 23
less than 50%	**17** & 19

Further we can compare the triadic results to the whole groups answering of the post-survey in line with expert's view. Whole groups answering percentages, which are in line with expert's view, are demonstrated in **Table 4**. It is to be noted that forming a cohesive answer in triad requires the same answer from all three members of triad which is a strict criterion for agreement. Therefore, **Table 1** and **Table 3** do not directly correspond to each other.

Comparing post-survey answering patterns relating to expert's view from triads (**Table 1**, **Table 2**, and **Table 3**) to whole group (**Table 5**) we can see many similarities. From **Table 4** we can see statements (1–6, 16, 18) in the highest triad consensus group respond quite well to the whole groups answering patterns resulting from a in line answering with the expert from 59% to all the way to 91%. Second triad consensus group questions are also well correlated to the whole study groups answering pattern reaching from (27%) 55% to 77% in line with the expert's view. Third and lowest consensus group is also having the lowest percentage of answering in line with expert's view ranging from (41%) 50% to 77%.

Statements in the 85% and more or 70–85% range (**Table 5**) were all included in the higher triad consensus groups (**Table 1** and **Table 2**) except interestingly question 21, which ranked less than 50% triad consensus, managed to score 77% expert aligned answers in the whole group.

This might be in contradiction with previous analysis that single detections are hard to link to particle like behavior. There might be a basic understanding of this particle-like behavior at a fundamental level, but in more complex situations, it becomes more challenging to comprehend, e.g., question 23, which scored very low percentages on both triad consensus and whole group answer pattern. We can also note that statements 7, 18, and 20 scored very low percentages within whole groups answers (**Table 4**) but settle relatively high on triad consensus (**Table 1**). Closer examination of question 18 and question 20 show that there might be confusion understanding the effect of localization on first slit R1 resulting in particle like distribution which is in line with the previous notion (**Table 2** and **Table 3**) that there is confusion related in predictability of particle like distributions. Also thought of "without interference pattern there is no pattern" might be reason behind challenges of this statement. Interestingly whole groups answers to statement 21 scored 77% expert-like answer while triad consensus was below 50%. This high expert-like view of the whole group indicates that there is some level of realization of the link between detection and particle nature of photons. Challenges of statements 17 and 19 within the whole group's answers are in line with triad results analyzed previously.

DISCUSSION AND CONCLUSIONS

Most important and interesting results provided in this study are based on the triadic analysis of agreed and disagreed statements. The key idea in the triadic cluster analysis method is to avoid averaging over the results, which masks subtle differences in individual answering patterns. The analysis method is based on probing similarities between answering patterns and then finding possible similarity classes among them. This way, we can uncover relevant information about the similarities of answering patterns, not easily available from the conventional correlation analysis. Triad has a of being an elemental group having thus a more significant role in group consensus formation than dyads would have (Koponen & Nousiainen, 2018; Turkkila & Lommi, 2020).

The respondents' way to use the photon state and photon concept in the post-survey indicate that around 66 % of answers were in line with the expert-view, thus indicating similarly coherent use of photon state concept as in case of experts. The positive generation from pre-survey to post-survey is evident in the formation of more expert-aligned clusters and the convergence of clusters as well as the whole groups overall more consistent expert-aligned answering. Results indicate that pre-service physics teachers who have gained more proficient view of photon as photon state have accessed to some attributes of quantum physics, allowing them to cross over the threshold from classical to quantum physics.

Interpreting the answering patterns found and their similarities reveals a degree of consistency in pre-service teachers' answers. This can be interpreted as a certain coherence, systematicity and rationality in answering patterns, which thus for each pre-service teacher contains more clearly agreed patterns and clearly disagreed patterns, and less mutually exclusive or contradictory choices. If one adopts the viewpoint based on mental models and assumes that we can make inferences about the mental model based on survey-like questionnaires and analyses of them, our results are interpretable so that pre-service teachers' mental models cannot be regarded as static; the results rather support the notion of the ontological flexibility and fluidity of mental models (Gupta et al., 2010). The context dependency of pre-service teachers' answers has also been observed in multiple previous studies (see, e.g., Ayene et al., 2018; Didic et al., 2014; Henriksen et al., 2018; McKagan et al., 2010) In the light of our results, and many others before us, it might be futile to try to find pre-service teachers' enduring mental models on quantum entities.

Another interpretation we can draw from the results is that pre-service physics teachers' choices stem from verbal descriptions and ways to express ideas, learned and recalled from previous encounters with textbook explanations and teachers' presentations. For example, the expression "to interfere with itself" is often well known to pre-service teachers, but its precise meaning (if it has such) is not so easy to conceive. This expression, nevertheless, is often used when they describe the behavior of photons in slits. On the other hand, the description of the patterns of single hits on the detector readily calls for expressions related to position, localization and so on, all easily connected with particle-like behavior. In this picture, the pre-service teachers' choices do not reveal so much about their mental models but rather the normative and coherent use of language (compare, e.g., with Stenhouse, 1986).

A control group was not used in the research, which may limit causal interpretations of the results. Nevertheless, the findings reveal at least a correlational relationship in the ways students use the photon concept, providing valuable insights.

The teaching intervention was quite short and that poses some limitations. Nevertheless, the results are promising and show positive trend in coherent use of the photon state concept. A longer teaching intervention could have facilitated a more significant change in learning consistent use of concepts and how to use them in normative way.

Changes in language can affect the way of thinking (e.g., photon) as a classical or quantum physical way. Even though we can describe quantum physical phenomenon with mathematics in a precise manner, the role of natural language interpreting and communicating these phenomena is crucial in learning, teaching and communicating experimental results. The use and creation of new concepts such as quanton is valid question to consider but what we want to highlight in our view is the importance of understanding the context where concept is used and its significance on the interpretation and utilization of the concept. Thus, the normative and correct use of concepts is essential when communicating and teaching about quantum physics.

In the future research, we intend to examine further how changing contexts affects pre-service physics teachers' use of key concepts and reasoning based on them. In doing so, we need methods that are sensitive to similarities and differences contained in answering patterns and allow us to classify the patterns in similarity classes. The analysis method applied here seems to provide a promising basis for developing such measures for uncovering subtle cues to coherent conceptions contained in the data, which are not easily captured by conventional correlation analyses. We believe that these analysis methods may complement and augment traditional correlation approaches in studies like ours. It seems that teaching quantum physics with quantum optics is a feasible way for pre-service physics teachers to learn about photons.

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Data availability: Data generated or analyzed during this study are available from the authors on request.

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APPENDIX A

Statements of the questionnaire and expert answer pattern with explanation provided in **Table A1**.

Table A1. Statements and expert answer pattern with explanation

	Statement		Expert answer pattern with explanation (A = agree, D = disagree)
Predictability			
1	Photon arriving at the slit R1 passes through slit R1 and its direction after the passage is predictable.	D	Descriptions "passing through" and "direction after passage" relates to realistic view since it refers to definite classical trajectory.
2	Directional distribution related to photon state after the slit R1 is predictable or distinguishable.	A	"Directional distribution" refers to quantum state perspective as it does not assume the photon has a definite classical trajectory but instead a probability distribution reflecting the superposition of the state and its projections. Term "photon state" relates to quantum view.
3	Arrival of photon either at a slit A or B of R2 is equally predictable.	A	Arrival refers detection at the slit that is predictable in the sense of probabilities and in this case equal since the system is symmetric.
4	Photon states related to slit A or B of R2 are equally probable.	A	"Photon state related" gives sense of mathematical description of the situation not a realistic event.
5	Direction of propagation of photon after R2 is predictable.	D	Direction of propagation of photon is not well defined and predicted.
6	Direction of propagation of photon state after R2 is predictable.	A	"Photon state" indicates predictability based on the quantum state of the system.
7	If the slit system R1 is allowed to move, no conceivable way to measure the "kick" of slit R1 allows predicting or detecting the photon's path.	A	Photon does not have distinct path in classical sense.
8	If the slit system R1 is allowed to move, no conceivable way to measure the "kick" of slit R1 allows predicting or detecting the photon state.	D	Photon momentum related to Heisenberg uncertainty and can give partial information about the photon state and help making predictions.
9	If the slit system R2 is allowed to move, it is possible to determine the photon state by measuring the "kick" of slit system R2.	D	Photon is in superposition so measuring R2 won't give exact information about the photon state.
10	If the slit system R2 is allowed to move, the path of the photon can be determined by measuring the "kick" of R2.	D	Photon does not have definitive "path" in quantum physics in the context of single photon double slit experiment.
Indistinguishability			
11	Photon arriving at the slit R1 either passes through without changing its direction or is absorbed by the slit.	D	Photon does not have definitive "direction" in quantum physics.
12	Photon state is localized in the slit R1. After the slit, photon state extends to a localized, ray-like narrow region, which extends from slit to the screen.	D	"Localization" indicates a precise location. In quantum perspective the photon can be localized only once when measured.
13	Photon passes through either slit A or B and both possibilities are equally probable. The final direction of the photon after slit R2 is due to scattering and changes in momentum as the photon interacts with the slit.	D	"Passing", "direction" refers to realistic classical trajectory.
14	Photon state localizes either in slit A or B, and both possibilities are equally probable. The final quantum state is due to scattering and changes in momentum as the photon state interacts with the slit.	D	"Localization" indicates a precise location. In quantum perspective the photon can be localized only once when measured.

Table A1 (Continued).

	Statement		Expert answer pattern with explanation (A = agree, D = disagree)
Self-interference			
15	Photon passes through both slits A and B and then interferes with itself. A new probability distribution of photon´s direction of propagation is created due to self-interference.	D	"Passing" refers to realistic classical trajectory. The interference pattern in quantum view is from superposition of path states rather than "self-interference" where something real is interfering with itself or other vague explanation on the description.
16	Localization of the photon state to slit A or B is equally probable. The final quantum state results from self-interference, which is a superposition of both possibilities.	A	Probabilistic view reflecting the symmetry of the experimental setup and also "photon states self-interference" is described as a superposition.
Single hits and interference pattern			
17	If photons passage through slit R1 is predictable or distinguishable, shape and extent of pattern of single hits on detector D can be predicted.	A	Predictability or distinguishability of "passage" relates to which-path information. Interference pattern is lost and resulting in particle like distribution which is predictable.
18	If photon state localization in slit R1 is predictable or distinguishable, the shape and the extent of the pattern of single hits on detector D can be predicted.	A	Photon state distinguishability relates to which-path information and destroys the interference and will provide a "particle like distribution".
19	If photons passage through slit R1 is predictable or distinguishable, the shape and the extent of the pattern of single hits on detector D can be predicted.	A	Same as in 17.
20	If photon state localization in slit R1 is predictable or distinguishable, the shape and the extent of the pattern of single hits on detector D can be predicted.	A	Photons state distinguishability destroys the interference and will provide a "particle like distribution".
WPD			
21	Possibility to register single hits shows that photons behave as particles when detected.	A	Discrete single hits on the detector signal a particle like behavior.
22	Formation of an interference pattern from single hits shows that photons behave as waves when detected.	A	Interference pattern is described as "wavelike" behavior.
23	Single hits on detector D show that photons exhibit a particle-like behavior in interaction with the detector.	A	Discrete single hits on the detector signal a particle like behavior.
24	Formation of an interference pattern shows that photons exhibit particle-like property in interaction with the detector.	D	Interference pattern is linked to "wavelike" behavior.

APPENDIX B

Detailed Description of the Course

For more information about the teaching intervention, see Koponen et al. (2025). The course was 7 weeks long, consisting of eight 90-minute lectures (two lectures a week) and two laboratory exercises and a visit to quantum computer in VTT (technical research center in Finland). The first laboratory exercise conducted was a single photon double slit experiment and the second Mach-Zehnder interferometer (MZI) with quantum eraser setup. The MZI experiment was not conducted with single photon statistics, but the outcome was discussed regarding the single photon situation.

Topics of the course were chosen in the light of the most recent surveys (Meyer et al., 2024; Merzel et al., 2024) and are listed in **Table B1**. The course was held at introductory level with requirement of only basic calculus provided by introductory physics courses. In the lectures there was heavy emphasize on connecting the lecture topics to real experiments from various research articles to provide an idea of the experimental apparatus and the operation related to it. The discussions of these experiments were elementarized to the introductory level and photon state view was clearly presented and used consistently throughout the lectures. Over simplified thought experiments were avoided. Dirac's bracket notation was introduced as a bookkeeping method in the spirit of Scarani et al. (2010).

Table B1. Topics of the course lectures and laboratory experiments (Koponen et al., 2025, p. 4)

L	Topics
1	Quantum physics. Didactic role in secondary level education. The most common quantum optics didactic experiment: DSE of single photons. Bohr-Einstein debate (of thought experiment).
2	Quantum theory of light and photon concept. Photon as quantized degree of freedom of electromagnetic field. Photon as quantum state (Fock-state). Dirac notation. Single photon interference in MZI (Grangier's, 1986 experiment). Interpretation in terms of photon states.
3	Which-Way experiments. Delayed-choice experiment. MZI and DSE versions. Quantum eraser experiments.
4	Quantum correlations and quantitative WPD as inequality relation. Distinguishability, predictability and visibility of quantum state. Connection to complementarity of conjugate variables.
X1	Laboratory: Single photon interference in DSE (count statistics & interference).
5	Interferometric experiments with electrons, atoms and molecules. Electrons as excitation of fermion-field. Description in terms of Schrödinger and Dirac's equation (briefly, basic idea only).
6	Bell's inequality (Clauser-Horne-Shimony-Holt form). Bell-states. EPR-experiment, Aspect et al. (1982) experiment. quantum state teleportation.
7	Qubits as registers. Quantum computing (simplest principles). Quantum cryptography (BB84 protocol). Bloch-sphere.
8	Quantum computers and quantum gates (basic). Quantum technologies (for quantum computers).
X2	Quantum eraser (semi-quantum) with diode laser, with MZI setup.