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Development of the mental models of wave and particle as basis for wave-particle duality

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Abstract. Wave-particle duality is included in many secondary school and university physics curricula as a concept central to quantum physics. The very term wave-particle duality suggests that a firm grasp of the individual classical concepts of wave and particle is crucial to studying quantum mechanics successfully. This raises the question whether students' mental models of these concepts are sufficiently addressed and developed prior to the teaching of wave-particle duality. We explored Dutch upper secondary school students' mental models of waves and particles using a short questionnaire. It was administered to a total of 147 students from two different groups. One group consisted of secondary school students prior to receiving formal education in introductory quantum mechanics while students from the other group had recently completed the Dutch national curriculum for pre-university education, which includes wave-particle duality. Our findings support the notion that students model classical particles and waves as mutually exclusive phenomena. Mental models of wave-particle duality, which require mixing the two classical models, appear to be only superficially developed. Our findings open avenues for future research on students' mental models of waves and particles as basis for wave-particle duality.

1. Introduction

Many experts in quantum mechanics (QM) research believe that wave-particle duality (WPD) should be a key concept in secondary school physics curricula [1]. Accordingly, the Dutch QM curriculum for secondary school reserves a central role for the concept of WPD and is well aligned with a traditional, historic approach to QM [2]. Regarding WPD, the syllabus for the Dutch curriculum [3] states that (translated from Dutch):

> *"The candidate can apply wave-particle duality in explaining interference phenomena for electromagnetic radiation and particles of matter, [specifically to] perform calculations with the de Broglie wavelength, describe the double-slit experiment and explain its meaning, [using] the terms probability and probability distribution, at minimum in the context of an electron microscope."*

When students are introduced to QM, specifically WPD, we (as teachers) may expect them to struggle or at least be surprised by the idea that something can have both particle and wave aspects. This expectation echoes the surprise and confusion felt by scientists at the beginning of the 20th century. Before the advent of QM, physicists regarded light and matter as belonging to distinct, mutually exclusive classes of physical phenomena. As QM developed, many have expressed difficulty accepting

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and understanding the dual nature of light and matter [4]. However, in the experience of present-day teachers, introductory QM rarely provokes a feeling of surprise or wonder in students from secondary and tertiary education alike, see, e.g., van den Berg et al. [5]. Only when students are explicitly pressed to carefully examine their reasoning about QM phenomena, they may experience a cognitive conflict [6]. As a colleague remarked when discussing WPD in class: "*The students did not show any surprise that electrons show wave behaviour.*" Even when the seemingly conflicting features of WPD are explicitly addressed by the teacher, there is no guarantee that students will fully grasp these ideas. The study by van den Berg et al. [5] suggests that student understanding is hindered by insufficient mastery of the classical concepts of wave and particle. While students know properties of waves (e.g., having a wavelength) and particles (e.g., having mass), they fail to recognize fundamental differences between the two phenomena. Hence, a further investigation of students' mental models of these concepts seems warranted.

2. Mental Models

The theory of mental models (MMs) stems from cognitive psychology [7]. An individual's MMs are internal representations of the external world, including concepts, phenomena, relationships, and systems. In learning situations, MMs facilitate the simplification and visualization of phenomena and the construction of analogies [8]. When confronted with unfamiliar domains, people use analogies from more familiar domains to make sense of new phenomena [9]. Hence, MMs change over time and hold value to the individual that constructed them. However, MMs are also resilient to change [10]. This may hinder learning. In the given context of QM, Baily & Finkelstein [11] point out that successful learning requires ontological flexibility where students actively mix old and new representations.

As we are interested in how students relate the new concept of WPD to their existing knowledge of physics, the theory of MMs provides a suitable framework for our research. However, as MMs are internal representations, we can only study the way that MMs are expressed by the learner. From these expressions we can acquire information about the MMs, but we can never access them directly.

Several studies have similarly used the theory of MMs to study learners' MMs of particles and wave phenomena as well as WPD. These studies often find that students use classical reasoning to explain quantum phenomena, occasionally mixing in (quasi)-quantum elements [12–17]. This is in line with the observation that students tend to add new elements to their existing MMs rather than replacing it with a new model. This raises the question which MMs exist prior to studying WPD and which information is added to these MMs by studying WPD.

3. Methods

3.1 Research question

Students' mental models of waves and particles should be sufficiently developed to study WPD effectively. Given the observation that students accept WPD as-is, seemingly without experiencing a cognitive conflict, we question which mental models (MMs) of waves and particles students develop prior to studying WPD and how new concepts are integrated into these models.
We question whether this is the case as students often don't express a mental conflict when introduced to WPD. Moreover, we question whether the teaching of QM and WPD changes students' MMs. These considerations lead to this study's main research questions (RQ):

> *RQ1: Which mental models of classical waves and particles do students express in upper secondary school physics?*
>
> *RQ2: How do students incorporate wave-particle duality into their existing mental models after studying wave-particle duality through introductory quantum mechanics in secondary school physics?*

3.2 Questionnaire design

From the perspective of MMs, we propose that students' comprehension of wave-particle duality hinges on the efficacy of their mental models and analogical reasoning. To elicit these MMs and study how

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these are influenced by introductory QM in upper secondary school, we developed a questionnaire. The questionnaire was inspired by a study by Johnston et al. [18] in which they asked third-year university students were asked *"what is a particle?"* and *"what is a wave?",* and subsequently used phenomenographic analysis to elicit student MMs.

The initial questionnaire stayed very close to Johnston et al. [18]. We considered the following questions (translated from Dutch):

Q1. What is a particle? Describe what you understand by it.
Q2. What is a wave? Describe what you understand by it.

Since these questions made no explicit reference to either classical or quantum phenomena, participants were free to decide which domain(s) they drew their answers from. However, when tested with a pilot group of secondary school students, we found that the responses remained very shallow, and saturation was quickly reached. Hence, we modified *Q1* and *Q2* to read:

Q1. What comes to your mind when considering the term particle?
Q2. What comes to your mind when considering the term wave?

This wording shwould allow students to associate more freely and provide more detailed answers. Additionally, taking a cue from van den Berg et al. [5], we added two more questions to highlight similarities and differences between the two main concepts of WPD:

Q3. What are similarities between a particle and a wave?
Q4. What are differences between a particle and a wave?

As *Q1* through *Q4* did not explicitly address QM, we included a fifth question specifically on WPD to check if students from the pre- and post-QM groups were familiar with WPD and its meaning:

Q5. Have you heard of wave-particle duality and if so, what does it mean according to you?

For all questions, we explicitly stated that answers could be as detailed as respondents felt necessary and offered the opportunity to add a drawing to written responses.

3.3 Selection of participants and data collection
To study the effect of QM teaching on student's MMs, we selected a pre-QM and post-QM group in 2023. The pre-QM group (N=44; two local secondary schools; questionnaires administered during regular classes) consisted of 15- to 17-year-old students enrolled in upper secondary school physics for the Dutch pre-university (VWO) track. Students from this group had not encountered QM yet as part of their physics education, as QM is typically taught just prior to the Dutch central exam in the final year of pre-university education. We expected the following peculiarities of the Dutch central curriculum to influence the student responses from this group:

- The electron is usually introduced with the subject of electricity and is generally treated as a particle in that context.
- The γ-photon is introduced when studying radioactive decay, usually well before QM. Whether the photon in this context is to be treated as a wave or a particle is unclear and presumably left up to the teacher to decide.
- Interference phenomena are not featured in the context of classical waves but only treated as part of QM.

The post-QM group (N=103) consisted of first-year university physics students and responses were generated by digitally distributing the questionnaire on the first day of the academic year, roughly four months after students had taken the secondary school central physics exam. This exam includes the subjects of QM and WPD. Participants had not yet received tertiary education regarding QM or WPD. On average, these students were 18 years old at the time of this study. Participants from this group come from a large variety of different secondary schools from all over The Netherlands. They have a shared background in the sense that there is a Dutch central curriculum for physics. However, how the subject is taught can differ between schools, though on average students spend about 20 hours in class studying QM in their exam year (excluding homework and exam preparation).

3.4 Data Analysis
We used a constant comparative method to perform a phenomenographic analysis to categorise responses and determine the relationship between these categories [19]. Thus, we first analysed responses to *Q1* and *Q2* and gathered sort-a-like items to become categories. Subsequently, we analysed *Q3* and *Q4* to clarify relationships between the categories. Categorizing items was repeated several times and various alternative categorizations were discussed before settling on a relatively small, tractable set of categories. In conjunction with the phenomenographic analysis, we performed a frequency analysis of each item in the various categories. Items which were both difficult to categorize and occurred with a frequency of less than 10% were discarded. We then arranged categories and their relationships into a concept map to illustrate the mental models expressed by students. Subsequently, we searched responses to all five questions for descriptions or mentions of WPD. In analysing these responses, we looked at what WPD was applied to, which experiments is was connected to and judged the quality of the description of WPD.

3.5 Ethical statement
This study has been approved by the University's ethical commission, letter of approval 3198.
Participants were briefed on the purpose of the study and signed an informed consent form for the data to be used for publication.

4. Results
4.1 Expressed mental models of classical wave and particle phenomena
Typical answers to *Q1* and *Q2* include *examples* (italics) as well as properties (underlined) of particle and wave phenomena, as shown in the following sample responses, one taken from the pre-QM group and the other from the post-QM group, respectively:

> "I think of a small part of a larger whole, like an *atom* or *molecule*"

> "[It's] a building block […] on the smallest scale we know, like a *proton* or *electron*"

Both responses show that a particle is believed to be very small, on the scale of molecules and smaller. Another broadly held believe is that particles can be combined to form larger structures, a property that we have termed combinable. We illustrate how responses to *Q3* and *Q4* add more detail to the descriptions of properties of both phenomena with the following two examples from the pre-QM and post-QM groups, respectively:

> "Both transfer energy when they collide with other particles or waves"

> "A wave doesn't have mass, a particle does. Particles don't have a wavelength"

Frequency analysis was used to recategorize or discard items or categories when their frequency was less than 10%. For instance, energy transfer did not rise above this 10% cut-off in either group. However, taken together with having energy the concept of energy did rise above the cut-off frequency. This frequency analysis indicated that the MMs expressed by students in their answers to Q1 through Q4 regarding classical physics are very similar in both the pre-QM and post-QM groups. The most notable difference occurred with wave phenomena; in the pre-QM responses, 63% of students mentioned sound as an example, compared to 26% in the post-QM group. We interpret this as a potential indication that the post-QM group, having received more physics instruction in general, is able to draw from a broader range of phenomena. However, we do not consider this difference in frequency to be evidence that the MMs of students differ significantly between the pre-QM and post-QM groups. Factors contributing to this include the limited sample size and the differences in how the pre-QM and post-QM groups were sampled. Overall, these findings indicate that students from both groups draw from a similar understanding of physical phenomena when expressing their MMs.

The expressed MMs of classical particle and wave phenomena are summarized through a concept map shown in figure 1. We chose to combine the data from both groups, warranted by the large overlap in responses. We have included the electron as a distinct example of a particle, rather than grouping it with other subatomic particles, due to its frequent role in discussions of WPD. The photon was also added to the diagram because its occurrence clearly exceeded the cut-off frequency. However, we positioned it between the particle and wave categories since it was about equally represented as a particle, a wave, or both. We've omitted interference from the diagram as at the time of our study it was only mentioned in the Dutch curriculum in relation to introductory QM.

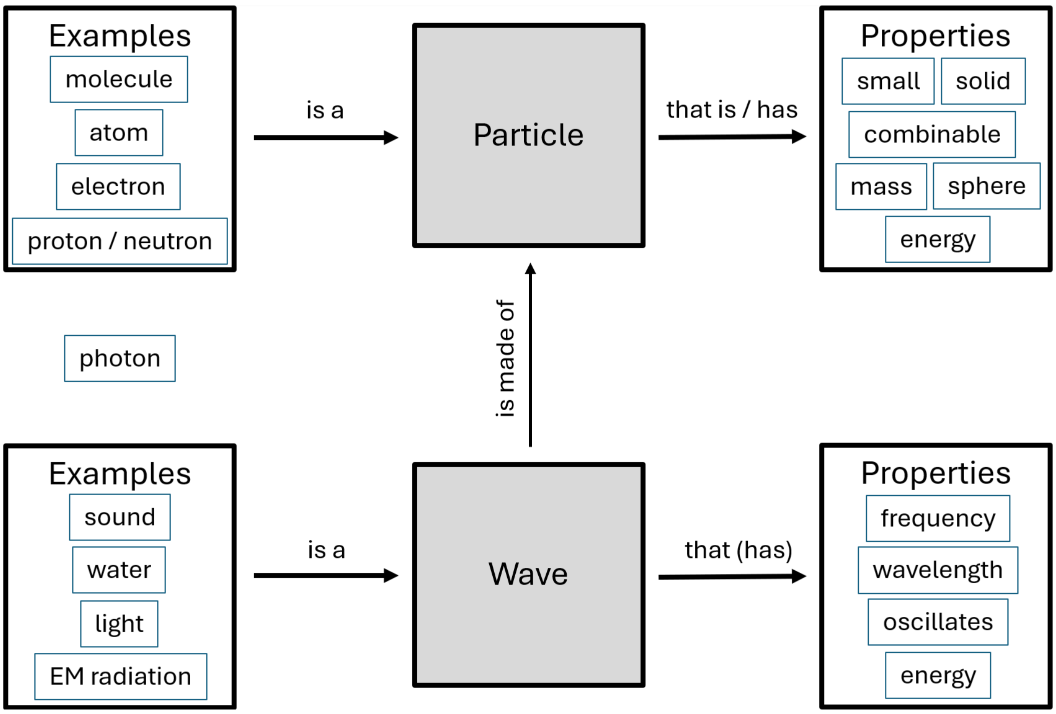

Figure 1. A concept map of wave and particle phenomena prior to studying introductory quantum mechanics education, constructed from student responses, to illustrate commonly expressed student mental models

4.2 Expressed mental models of wave-particle duality

A total of eight students from the pre-QM group expressed some knowledge about WPD, by explaining that light shows both particle and wave behaviour in the double slit experiment. One student from this group also mentioned the electron. As most of these students clarified that they had learned about WPD outside of physics class, we won't include the pre-QM group in our further analysis of WPD.

We categorized responses from the post-QM group, regarding WPD (*Q3* through *Q5*) and performed a frequency analysis. The results of this analysis are summarized in table 1, where frequencies are reported as percentages rounded to the nearest 5%.

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Table 1. Aspects of WPD in student responses

Aspect of WPD	Frequency
Both wave and particle aspects for:	
- Particle (undefined)	40%
- Light (general)	20%
- Photon (specific)	20%
- Electron	20%
Interference (standalone):	
- mentioned	5%
- linked to WPD	<5%
Double slit experiment:	
- without interference pattern	20%
- Including interference pattern	15%
The photo-electric effect:	
- mentioned	5%
- linked to WPD	<5%
Relevant aspect depends on:	
- Circumstances (unspecified)	5%
- Measurement or observation	10%
- Particle size	5%

We found that ~40% of students mentioned WPD spontaneously when answering *Q3* or *Q4*, which address the similarities and differences between particles and waves, respectively. This suggests that for many students, WPD has become an active part of their MMs of wave and particle phenomena after studying introductory QM.

After also considering the responses to *Q5*, we found that 90% of respondents from the post-QM group showed at least some familiarity with WPD by mentioning one or a combination of the items from table 1. In 40% of cases, the specific particle or wave phenomenon to which the student applied WPD was not specified, as illustrated by the following example:

> “At a certain scale, a particle can behave as a wave”

In cases where students did elaborate, they applied WPD to light, photons or electrons, as illustrated by the following responses:

> “I think of light, which propagates as a wave but transfers energy like a particle.”

> “In quantum mechanics, photons can have both wave and particle properties.”

> “Electrons are usually particles, but sometimes they briefly behave like a wave.”

The double slit experiment was often mentioned in relation to WPD, sometimes clarified by describing the formation of an interference pattern. Interference was mentioned regularly as a wave phenomenon but not always clearly linked to WPD.

Rarely, the photo-electric effect was mentioned, either by name or through describing the process of quantized energy transfer from a photon. Only three students connected the effect correctly to WPD by explaining how it demonstrates the particle properties of a photon.

Only a small number of students explained what determines whether the wave or particle aspect should be considered, stating that it depends on either experimental conditions, the presence of a measurement device or a particle's size.

5. Discussion and conclusion

In this study we investigate which mental models about classical waves and particles students typically express prior to them studying introductory quantum mechanics in secondary school. We also investigated how students incorporate the concept of wave-particle duality into their existing mental models. To this end, we compared responses to a questionnaire administered to one group prior to studying introductory quantum mechanics and another group that had already completed it. The goal was to elucidate the influence of introductory quantum mechanics education on student understanding of wave-particle duality.

5.1 Expressed mental models of classical wave and particle phenomena

Based on responses from both groups of students, we conclude that their expressed mental models treat wave and particle phenomena as distinct and mutually exclusive in the context of classical physics. The two domains are connected by the broadly held believe that waves emerge from the collective behaviour of individual particles. A particle is typically described as a small, spherical entity of a certain mass or energy. Single particles can be combined to form larger particles, as demonstrated by subatomic particles forming atoms, atoms forming molecules and so on. We note that this is not true for photons. For students that model photons as particles, this could one source of an unresolved cognitive conflict.

5.2 Incorporating wave-particle duality

Mostly all students from the group that had completed introductory quantum mechanics had some recollection of wave-particle duality four months after completing the Dutch secondary physics exam. Usually, they expressed that wave-particle duality is a quantum mechanical concept where, e.g., photons or electrons have both wave and particle properties. Wave-particle duality is often associated with the double slit experiment where an interference pattern is produced. We note that this is an example of photons or electrons showing wave properties. How the particle aspects of photons or electrons can be demonstrated was only explained by one out of a hundred students, using the photo-electric effect as an example. Thus, we suspect that the concept of wave-particle duality, though added to students' mental models of physical phenomena, is only partially understood by students.

5.3 Limitations and suggestions for future research

Although we have gained several valuable insights from responses to the questionnaire, we have only been able to superficially probe students' mental models. To gain additional insights and depth of understanding, follow-up interviews should be conducted with students. For instance, it would be of interest how students make sense of atoms or molecules being combinable particles while simultaneously showing interference phenomena, which is a wave property rather than a particle property. Likewise, how do students make sense of photons being labelled particles and which classical concepts are they willing to abandon, considering new experimental evidence, if any concepts at all? In any case, it is not fully clear from our research to which extend students truly understand wave-particle duality, if at all.

5.4 Implications for teaching

Based on student responses from both groups, we constructed a concept map of classical wave and particle. Although each individual student will have their own mental model of these phenomena, we expect that this concept map outlines a basic set of ideas commonly shared within the classroom. Teachers can use this as a foundation at the start of the treatment wave-particle duality in introductory quantum mechanics. By explicitly addressing students' models of classical phenomena, it may be possible to demonstrate the conflict between classical and quantum physics more clearly to students.

The double slit experiment is a hallmark of introductory quantum mechanics, as is the photo-electric effect. However, our data suggests that it is only the double slit experiment which is added to students'

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mental models of wave-particle duality, mainly stressing the wave aspect of it. As such, the notion of duality seems to be lost and not really understood by students. It may be possible to remedy this, at least in part, by explicitly addressing the link between the photo-electric effect and the particle aspects of light. This can be extended to other experiments to clearly show both the wave and particle aspects of electrons.

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