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Prior knowledge of potential energy and the understanding of quantum mechanics

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Abstract
Quantum mechanics (QM) has become part of many secondary school curricula. These curricula often do not include the mathematical tools for a formal, mathematical introduction of QM. QM therefore needs to be taught at a more conceptual level, but making secondary school students understand counterintuitive QM concepts without introducing mathematical formalism is a challenge. In order to accept QM, students not only have to see the need of it, but also have to see that QM is understandable and logical. Dutch secondary school students are familiar with potential energy (PE) in the context of gravitational and elastic energy. Therefore, the introduction of QM by using the potential wells and tunneling with emphasis on students' prior knowledge of PE could be a way to make QM more understandable and logical. To explore this, we investigated the relation between the understanding of energy diagrams and the understanding of the potential well and tunneling. A module was created to promote students' understanding of PE in classical context. Then, a quasi-experimental intervention was used, in

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which the experimental group received additional lessons using the module on classical energy diagrams before being taught QM. Two tests were developed in order to determine students' understanding of PE and QM. The results of the tests showed that the experimental group not only had better understanding of PE diagrams, but also of QM even before they were being taught QM. Analysis of the tests also showed that there was a significant correlation between the understanding of PE diagrams and the understanding of QM. Therefore, the results of this study indicate that emphasis on PE can be used to reduce the gap between students' prior knowledge and QM.

Keywords: secondary school, quantum mechanics, potential energy

Supplementary material for this article is available online

1. Introduction

In recent years, quantum mechanics (QM) increasingly has become part of secondary school curricula [1]. Since QM is rather abstract and counterintuitive, this has resulted in an increased interest into the investigation of methods for introducing QM at a more conceptual level [2]. Recent research into the introduction of QM at the secondary level has focused mainly on better understanding of students' difficulties regarding the counterintuitive wave-particle duality [3–9], and some research has focused on two-level quantum states [10, 11]. Another way of introducing QM, which has been investigated less frequently, is to introduce the infinite 1D potential well and tunneling [12]. The potential well and tunneling have been investigated for the undergraduate level [13–15]. However, even though experts consider this topic important [16], there has been little research into secondary school students' understanding of the potential well and tunneling [17]. The introduction of the wave behaviour of quantum entities by using the potential well seems rather abstract and difficult for students to understand. But, in contradiction to the wave-particle duality, the potential well offers ways of approaching QM that are already familiar to secondary school students in the classical context. Students already are familiar with other forms of potential energy (PE), such as gravitational and elastic energy, which can be more easily connected to real-life experiences than QM. Therefore, this approach could be used to create better understanding of QM in terms of energy, by reducing the gap between students' prior understanding and QM. Research shows that several difficulties in learning QM are related to students' inability to interpret PE diagrams [18]. Therefore we have investigated if students' understanding of QM is influenced by their prior knowledge on PE diagrams.

2. Theoretical background

When learning classical mechanics, students have learned about particles and waves, which are intrinsically different concepts. Particles have properties such as position, mass and size, whereas waves have properties such as wavelength and amplitude. In QM an electron can have both particle and wave properties, which is inconsistent with students' prior learning. From the perspective of learning theory, this raises difficulties. According to Chi [19], there are three ontological categories; entities, processes and mental states. Robust misconceptions occur when new concepts are miscategorised and students need to 'move' a concept from one ontological category to another. Since particles belong to the ontological category 'entities' and waves to the category 'processes', there is a need for a new ontological category for learning QM. Students need to embrace a new, flexible, ontology [20], in which the quantum entity can have particle or wave properties, depending on the context. The need for this new ontological category, and the overlap with students existing ontological categories makes learning QM a complex process.

In conceptual change theory, the most common conceptual change strategy is to create a cognitive conflict [21], which shows that students' prior thinking is incorrect. Therefore, many research focuses on showing the conflict of the double slit experiment with students' expectation based on prior, classical, knowledge in order to show students the need of a new theory. But according to Posner *et al* [22]., in order to create conceptual change, this new theory needs to be understandable, logical and useful. So, even when students see that classical mechanics is not capable of explaining quantum phenomena, they still need to accept that QM does explain it. In order to make QM understandable, logical an useful, students need to see that some previously learned concepts still apply in QM. To promote conceptual change, Vosniadou and Skopeliti [23] propose to design curricula aiming to reduce the gap between students' prior knowledge and the new knowledge. Upper-level secondary school students are familiar with PE in the context of gravitational and elastic energy, and they are able to relate this to real-life experiences. Therefore, introducing a model system, such as the 'infinite potential well' and connecting it to compatible prior knowledge on energy diagrams could be a way to reduce the gap between initial knowledge and QM. At the undergraduate level, there has been some research into students' understanding of PE and atomic-molecular interactions. Becker and Cooper [24] observed several intuitive and incorrect interpretations of PE. They concluded that it is important to promote prior knowledge of PE and help students to make connections between PE and atomic-molecular interactions. Additionally, research into students' understanding of QM [18] showed that students have several difficulties in understanding the PE diagrams of the 1D infinite potential well and tunnelling. Therefore, in this study we investigated the influence of understanding of PE on the understanding of QM, aiming to answer the following questions:

(a) Can we improve students' understanding of PE?
(b) Is there a relation between the understanding of PE and QM?
(c) Does an increase in understanding of PE lead to a better understanding of QM?

3. Method

In order to make it easier to relate QM to prior knowledge of energy diagrams, instructional materials were developed to promote students' prior knowledge of energy diagrams in a classical context. A quasi-experimental intervention was conducted at Dutch secondary schools, in the final year of pre-university education. Teachers of ten different secondary schools were willing to participate in our study. Thirteen classes ($N = 234$ students) were used as experimental groups, 11 classes ($N = 157$) as control groups. In order to create difference in understanding between the experimental and control groups, instructional materials on PE were created. Tests were used to compare students' understanding of PE and QM.

3.1. Creation of instructional materials

We developed a module regarding PE and energy diagrams as an addition for teaching QM. The module was created in order to; (a) refresh students' knowledge on gravitational energy, elastic energy and electric energy, (b) explain that these are all types of PE, and (c) learn students to interpret energy diagrams in terms of velocity, position, and force. The materials were pre-tested with a small group of secondary school students.

Evaluation with a preliminary pre- and post-test gave a first indication that students had more knowledge of PE after they worked with the materials. Based on student and teacher feedback, the materials were adjusted. A schematic overview of the final module can be found in table 1, the complete module can be found in appendix A (available online at stacks.iop.org/PED/57/025012/mmedia).

3.2. Description of the tests

To determine students' understanding of PE diagrams, potential wells and tunneling we created two tests; (a) a PE test regarding students' understanding of energy and (b) a QM test regarding students' understanding of the potential well and tunneling. The PE test focused on the ability to relate energy and energy diagrams to the position and velocity of, and forces working on an object. The test consisted of 13 questions in four different contexts (see appendix B). The QM test on potential wells and tunneling consisted of seven questions; three questions regarding the potential well and five questions on tunneling. The QM test

Table 1. Overview of the module on PE and energy diagrams.

Chapter	Themes
1. Introduction	Work and energy
	Law of conservation of energy
2. Earths' gravitation	Gravitational force and energy on earth
	Example: the height of a ball
	Advanced exercises: roller coasters
3. Elastic energy	Elastic force and energy
	Example: a mass-spring system
	Advanced exercises: bungee run and bungee trampoline
4. Universal gravitation	Gravitational force and energy
	Example: a satellite launch
	Advanced exercises: space probes and manned space travel
5. Force and PE	Comparison of a *F,x*- and *E,x*-diagram
6. Electric energy	Force and energy of two point charges
	Force and energy in a homogeneous electric field
	Advanced exercise: alpha decay

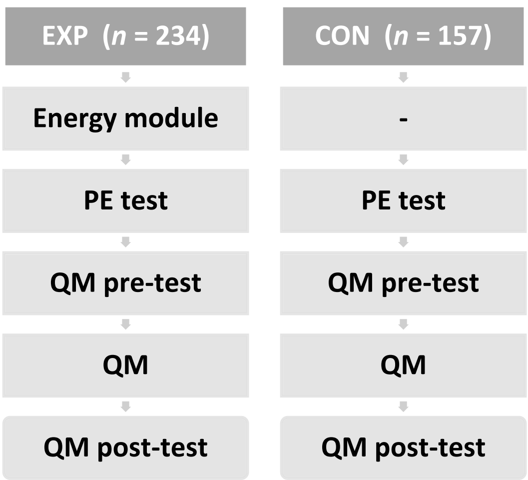

Figure 1. Experimental procedure.

focused on the ability to relate the PE diagrams to probability, kinetic energy and total energy. The questions of the QM test can be found in appendix C.

Table 2. (a) Pattern matrix of the PE test. (b) Pattern matrix of the QM test.

(a)

	Component		
	E1	E2	E3
EN1		.66	
EN2		.66	
EN4		.50	
EN5			.70
EN7			.63
EN8		.36	
EN9			.44
EN10	.87		
EN11	.88		

(b)

	Component	
	Q1	Q2
PO1		.74
PO2		.60
PO3		.67
PO4	.67	
PO5	.57	
PO6	.68	
PO7	.77	
PO8		.42

3.3. *Procedure*

The module and tests were used at ten different secondary schools, in the final year of pre-university education. The group sizes varied between 14 and 28 students. The quasi-experimental intervention consisted of the implementation of the energy module and the use of the energy and QM test (see figure 1). The experimental groups ($N = 234$, 13 classes) worked with the module and then took the tests, the control

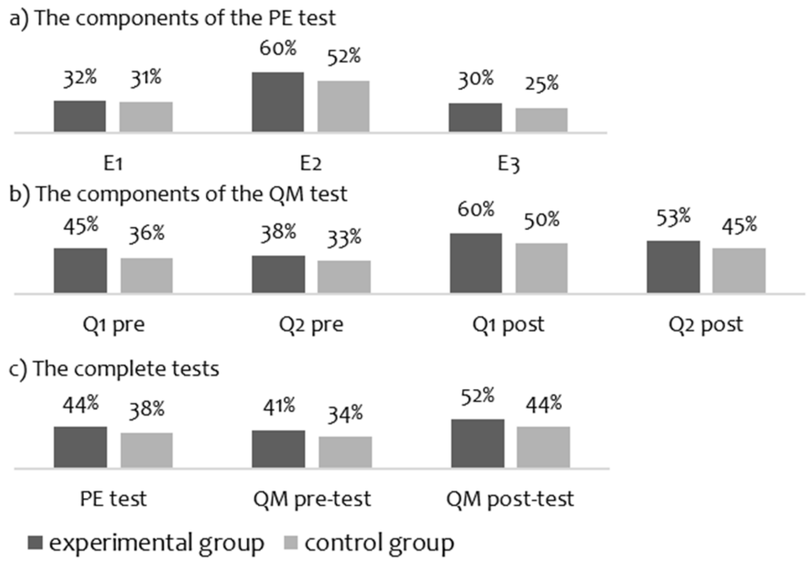

Figure 2. Scores of the experimental and control group.

groups ($N = 157$, 11 classes) immediately started with the tests. After the students had taken the energy- and pre-test, teachers would go back to their normal program of teaching QM. The books and methods used for teaching QM varied for the different teachers and schools. Afterwards a post-test was given to determine students' final understanding of potential wells and tunneling.

3.4. Data analysis

In order to investigate if the developed tests could be used to determine understanding of the three different aspects of the understanding of PE and the understanding of QM, we did an explorative factor analysis using principle component analysis [25] (PCA). PCA is a method for dimension reduction, which can be used to reduce a large set of correlated variables into a smaller set of unrelated principal components. These principal components are linear combinations of the original variables. To explore the differences in understanding of PE and QM between the experimental and control group, we performed an independent sample t-test of the different tests, and calculated the effect size [26]; Cohen's d. The p-value of the t-test will give information on the existence of a significant difference, the d-value will give information on the size of this difference between the experimental and control group. The relation between the understanding of PE diagrams and the understanding of potential wells and tunneling, was investigated by calculating the Pearson correlation coefficient between the results of the tests, and conducting a path analysis [27]. A path analysis is a visual representation of the different variables, in which the regression coefficients of the different relations between these variables are shown.

4. Results

4.1. Test evaluation with principal component analysis

A PCA was used to analyse the tests. During the analysis of the PE test, four questions were found to be outliers and were omitted. The analysis showed that the remaining PE test consisted of three components (see table 2(a)). These components were in line with the content of the questions:

- Component E1: understanding of the relation between PE and force;
- Component E2: understanding of the relation between PE and position;
- Component E3: understanding the relation between PE and movement or velocity.

Table 3. Results of the independent sample t-test for the scores of the experimental and control group.

			Group		*T*-test		Effect size
			EXP	CON	*t*-value	*p*	Cohen's *d*
Components of PE test	E1	M	.32	.31	.26	.797	0.03
		SD	.40	.39			
	E2	M	.60	.52	3.74	.000	0.39
		SD	.22	.21			
	E3	M	.30	.25	2.12	.035	0.22
		SD	.25	.23			
Components of QM pre-test	Q1	M	.38	.33	1.55	.122	0.16
		SD	.29	.28			
	Q2	M	.45	.36	3.37	.001	0.34
		SD	.25	.28			
Components of QM post-test	Q1	M	.51	.44	2.12	.035	0.22
		SD	.34	.33			
	Q2	M	.53	.45	2.46	.015	0.25
		SD	.29	.31			
Complete tests	PE test	M	.44	.38	3.48	.001	0.36
		SD	.17	.15			
	QM pre-test	M	.41	.35	3.19	.002	0.33
		SD	.20	.22			
	QM post-test	M	.52	.44	2.80	.005	0.29
		SD	.26	.256			

Table 4. The correlation between the understanding of energy and QM.

			Components of QM pre-test		Components of QM post-test		Complete QM test	
			Q1	Q2	Q1	Q2	Pre	Post
Components of PE test	E1	*r*		.13			.12	
		Sig.		.008			.023	
	E2	*r*		.29	.13	.27	.20	.24
		Sig.		.000	.013	.000	.000	.000
	E3	*r*			.12			.11
		Sig.			.019			.034
Complete PE test		*r*		.27	.15	.20	.20	.21
		Sig.		.000	.002	.000	.000	.000

For the PCA of the QM test, we used the results of the post-test. The PCA resulted in two components (see table 2(b)) which were reasonably consistent with the content of the questions:

- Component Q1: understanding of the influence of tunneling on energy and probability;
- Component Q2: understanding the relation of PE to energy and probability.

The components found in this analysis were used in the further analysis of students' understanding.

4.2. Differences between the experimental an control group

To determine the differences in understanding of the experimental and the control group, we analysed the test scores for the questions categorised into the different components found in the previous paragraph. The students' scores for the different tests are shown in figure 2. As can be seen, the experimental group outperformed the control group, both on the separate components as on the complete tests. An independent-samples *t*-test was conducted to compare the scores of the experimental and control group. The results of the *t*-test and the effect sizes are shown in table 3. The *t*-test showed that there was a significant difference in understanding between the experimental and control group for component E2 and E3 of the PE test, Q2 of the pre-test and Q1 and Q2 of the post-test. Also can be seen that there is a significant difference in understanding for all the complete tests. However, the effect sizes are relatively small.

4.3. Relation between the understanding of energy diagrams and the understanding of potential wells and tunneling

In order to analyse if there is a relation between the understanding of PE diagrams and the understanding of potential wells and tunneling, we calculated the Pearson correlation coefficient between the results of the tests. The results (table 4) show that there is a significant, but relatively small, correlation between the scores of the PE test and the scores of the QM test, especially for component E2: the understanding of the relation between PE and position.

To examine the relation between the understanding of the different aspects of energy diagram more thoroughly, a path analysis was conducted. In figure 3 the grey arrows show the regression coefficients of the three components of the PE test for the results of the QM pre-test. This represents the influence that the different components have on the prior knowledge of QM. The black arrows show the regression coefficients of the three components of the PE test and the pre-test for the results of the QM post-test. This represents the influence of the prior understanding of energy diagrams and QM on the final understanding of QM. This figure shows that students' score for interpreting energy diagrams in terms of position has de largest direct and indirect influence on the final understanding of QM.

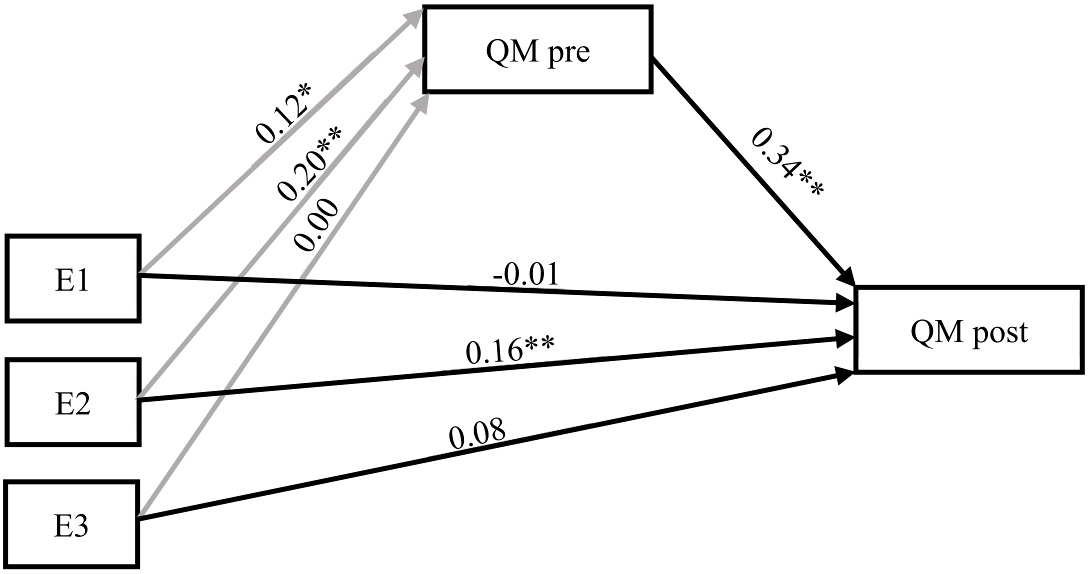

Figure 3. A path analysis of the understanding of energy diagrams, prior and final understanding of QM.

5. Conclusions

5.1. The relation between the understanding of potential energy and quantum mechanics

We have investigated the relationship between the understanding of energy diagrams and the understanding of the potential well and tunnelling. Analysis of a PE test and a QM test showed that there was a significant difference in understanding between the control and experimental group. The experimental group scored significantly better on the PE test and on the QM pre- and post-test. Remarkable was the fact that the experimental group had better understanding of QM even before students were taught QM. These results clearly show that QM understanding is supported by a good understanding of the classical concept of PE.

When looking at the different components of the understanding of energy and the understanding of QM, there was also a significant difference in test scores. The experimental group scored significantly better on their understanding on energy diagrams in terms of position (E2) and velocity (E3). However, no significant difference was found for the understanding of energy diagrams in terms of forces acting on an object (E1). Analysis of the two components of the QM test showed that the experimental group scored significantly better on the understanding of the relation of PE to energy and probability (Q2) in the pre- and post-test. For the understanding of tunnelling (Q1), there was only a significant difference for the scores on the QM post-test.

The analysis of the Pearson correlation between the different components of the energy and QM test showed that there was a significant correlation between the scores on the energy and the QM pre- and post-test. The most prominent correlation was found between the understanding of energy diagrams in terms of position (E2) and the understanding of the relation of PE to energy and probability (Q2). The path analysis confirmed that the understanding of energy diagrams in terms of position had the greatest influence on the understanding of QM before and after QM instruction.

In this investigation we have seen that students who received additional lessons on PE scored significantly better at the QM test. We also have seen that there is a significant correlation in students' understanding of PE and QM. Therefore, we can conclude that an increase in understanding of PE diagrams does lead to better understanding of QM. Knowledge of PE has a distinct and significant influence on the understanding of QM. The results therefore suggest that understanding PE is an important part of understanding the potential well and tunnelling, and can be used to reduce the gap between students' prior knowledge and QM.

5.2. Limitations and implications of this study

The intervention used in this study consisted of providing instructional materials on PE, without teacher training or instructional materials relating PE specifically to QM. Additionally, the books and methods used for teaching QM varied for the different teachers and schools. This may have influenced the outcomes of this study and diminished the effect sizes and correlations. However, this leads to the expectation that effects might be even higher when performing the intervention under more controlled conditions.

This leads to an opportunity for researchers in the field of QM education. This study shows that there is a relation between understanding PE and QM, but the materials used in this study are not yet refined and optimized. In order to improve QM teaching at the secondary school level, there is a need for design-based research. Materials, stimulating knowledge of PE, need to be designed, implemented, analysed and improved. There is also a need for research in which is investigated how QM can be adequately connected to students' prior knowledge on PE. Additionally, the role of the teacher should be taken into consideration. Teachers could play a major role in connecting QM to students' prior knowledge. Teachers should be aware of this, not only in the context of QM, but for teaching physics in general.

This research also has implications for curriculum development in physics education. It shows the importance of prior knowledge for learning QM and for physics in general. Additionally, this research showed the importance of students' understanding of energy, which is a central concept in physics. This raises the question of the importance of the central concepts of physics (e.g. energy, force, and momentum) for the understanding of other topics. More emphasis on these central concepts within the physics curriculum, as binding principles between all physics domains, could increase cohesion, and may lead to students that are more aware of the nature of physics and have deeper understanding. Therefore, curriculum developers need to consider: (a) what prior knowledge is needed for the different topics within the curriculum, and (b) how the different topics in the curriculum are related to the central concepts of physics. A curriculum in which the topics build on previous topics and in which connection between related topics are made, will lead to better physics understanding.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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