Research Article https://doi.org/10.12973/eu-jer.12.3.1247

European Journal of Educational Research
Volume 12, Issue 3, 1247 - 1255.
ISSN: 2165-8714
https://www.eu-jer.com/

Classical Mechanics Key Topics in Physics Teacher Education: Results of an Exploratory Mind Map Study

Bianca Winkler
Friedrich-Alexander-Universität Erlangen-Nürnberg, GERMANY

Joaquin Veith
University of Hildesheim, GERMANY

Philipp Bitzenbauer*
Leipzig University, GERMANY

Received: February 1, 2022 ▪ Revised: March 25, 2023 ▪ Accepted: April 12, 2023

Abstract: Although the central role of classical mechanics in physics teacher education is undisputed, divergent interests and perspectives from different disciplinary cultures might exist when thinking about how to best support pre-service teachers' professional development. In this article, we report the results of an exploratory mind map study to investigate which classical mechanics topics are regarded essential for physics teacher education according to N = 29 experts from different physics disciplines. The participants' mind maps were analyzed using a category system and frequency analysis was applied. The results hint at similarities and differences in terms of key topics to be addressed in physics teacher education on classical mechanics according to experts from different physics disciplines, e.g., in terms of the depth of mathematics considered relevant for physics teacher education.

Keywords: *Classical mechanics, exploratory study, mind-map, teacher education.*

To cite this article: Winkler, B., Veith, J., & Bitzenbauer, P. (2023). Classical mechanics key topics in physics teacher education: Results of an exploratory mind map study. *European Journal of Educational Research, 12*(3), 1247-1255. https://doi.org/10.12973/eu-jer.12.3.1247

Introduction

Galili (1995) describes how learning mechanics may influence students' understanding of various physics concepts in different fields by stating: "A huge edifice, which today we call physics, consists of various domains. The importance of mechanics is more than just being one of these domains. It determines the 'rules of the game', defines the main tools in physics, and presents the most universal laws of nature. It actually describes the method of the discipline of physics which is then applied in all other domains in this discipline. This is why mechanics always opens any physics curriculum" (p. 371). Similar arguments have been brought forth by Carson and Rowlands (2005) who identify mechanics "as the logical point of entry for the enculturation into scientific thinking" (p. 474). Friege and Lind (2004) argue that mechanics is an important basis for gaining an insight into further areas of physics and that it may even be regarded a useful predictor of physics knowledge in general. Therefore, it is hardly surprising that classical mechanics is mostly taught at the beginning of physics classes in schools or in physics study programs (Hestenes et al., 1992) – Galili and Goren (2022) even consider classical mechanics to be "the most fundamental theory that students encounter in school" (p. 3). Given its fundamental importance in (school) physics, classical mechanics is a key component of physics teacher education programs (Callahan et al., 2009).

With regards to the development of pre-service physics teachers' content knowledge (see Baumert et al., 2010; Shulman, 1987), factors that influence the learning of classical mechanics have been investigated so far (Champagne et al., 1980). However, the question of which specific key concepts of classical mechanics should be included in physics teacher education remains an ongoing inquiry. The answer to this question may vary between different physics experts as has already been indicated for different physics domains: In the context of quantum physics, for example, previous research has shown that it may be difficult to reach consensus among experts from different physics disciplines on the topics to include in introductory courses (Krijtenburg-Lewerissa et al., 2019; McKagan et al., 2010). Similarly, the view of the role of mathematics in the study of physics at university differs both among lecturers and pre-service physics teachers (de Winter & Airey, 2022).

An exploration of commonalities and differences in the content-foci regarding classical mechanics to be covered in physics teacher education across experts from different physics disciplines is lacking in the literature so far. However,

* **Corresponding author:**
Philipp Bitzenbauer, Institute of Physics Education, Leipzig University, Leipzig, Germany. ✉ philipp.bitzenbauer@uni-leipzig.de

obtaining input on classical mechanics key concepts for physics teacher education from experts with diverse backgrounds seems valuable for informing curriculum development in teacher education programs and promoting communication among physics lecturers with different research backgrounds.

With this article, we contribute to closing the above-mentioned gap by presenting the results of an exploratory study to approach the clarification of the following research questions:

1. Which are the key topics of classical mechanics to be covered in physics teacher education according to experts from different physics disciplines?
2. Which differences regarding the content foci in physics teacher education on classical mechanics exist between experts of different physics disciplines?

Methodology

Study Design and Data Collection

In this study, a qualitative approach was taken. To collect key topics of classical mechanics to be covered in physics teacher education, the mind map method was chosen (see Crowe & Sheppard, 2012). The study participants (for details on the sample, see below) were asked to prepare mind maps on classical mechanics topics that are relevant for physics teacher education from their point of view. More specifically, the experts were asked to (a) group terms and aspects that are decisive for the different key topics, and to (b) organize them through appropriate connections. The mind map method seems a sensible approach for a clarification of our research questions since mind maps "paint an external picture of what is going on inside" (Buzan & Abbott, 2017, p. 61) the experts. In particular, the process of creating a mind map has been described to be more productive than other eligible data collection techniques (see Winkler et al., 2021): For example,

- in contrast to asking participants to list the most relevant topics of classical mechanics for physics teacher education, the task to create a mind map is likely to better help the participants organize their thoughts.
- while the participants' thoughts are influenced by the questions posed when employing more guided data collection techniques, such as interviews or questionnaires, the preparation of mind map allows for a natural process without influencing the participants.

An in-depth analysis combining categorization and frequency analysis of the terms used in the experts' mind-maps (for details on the data analysis, see below) allowed for an exploration of the classical mechanics key topics to be covered in physics teacher education according to experts from different physics disciplines. For the mind-map generation, prepared answer sheets were given to the participants to ensure the standardization of the implementation and the anonymization of the procedure.

To ensure the reliability of the mind map method, we provided clear instructions and guidelines for creating the mind maps (as described in the standardization of the implementation section above), and had independent researchers review and analyze the mind maps using a coding scheme (details of which can be found in the data analysis section below). To ensure the validity of this research, we collected data from four different physics disciplines to ensure a broad range of content perspectives (for a description of the study sample see the next subsection). Additionally, we allowed participants ample time to complete their mind maps.

Participants

N = 29 physics professors and postdocs participated in the study. Each of the participating researchers works in one of the four fields astrophysics (6 experts), condensed matter (9 experts), optics (3 experts) or theoretical physics (11 experts). Hence, the researchers in these four pillars deal with thematically different physics subfields. The 18 experts in astrophysics, condensed matter, and optics are all experimental physicists. The restriction of our sample to professors and postdocs ensures that only researchers who have already worked intensively in one of these physics areas are interviewed so that it can be assumed that they are accustomed to a specific subject culture. Additionally, all our study participants had held at least one physics course within a physics teacher study program before taking part in this study.

Data Analysis

To approach a clarification of research question 1, a frequency analysis of the terms used by the experts for the mind map preparation was carried out. We identified a topic represented in the mind maps as a key topic of classical mechanics for physics teacher education if and only if at least 20% of the researchers in the total sample included it in their mind map as has been done in similar studies before (see Winkler et al., 2021). In this analysis step, terms that cover the same content aspect (e.g., the terms Hamiltonian and Hamilton operator) were merged and counted as one. The frequency analysis has been conducted for both, (a) the total sample, and (b) split according to the study participants' physics disciplines.

The mind map terms were then categorized using an inductive procedure to approach a clarification of research question 2. In total, the categorization led to a coding scheme comprising six categories. To provide a differentiated overview, each category has been divided in several sub-categories (for the category system see Figure 3). Two independent raters carried out the final coding with a high level of agreement (Cohen's $\kappa = 0.89$).

After, the mind map terms used by the respondents were assigned to the corresponding categories, an analysis of the occurrence of the different (sub-)categories divided by the respondents' subject areas was conducted. This approach enables to uncover whether different mechanics topics, i.e., (sub-)categories, are given different priority for physics teacher education by the representatives of the different physics disciplines. We followed Winkler et al. (2021) and identified a focus in the perspective of researchers from a specific discipline on category X if more than 15% of all terms in the mind maps of the test persons from this subject area could be assigned to category X. In this study, we refrained from analyzing connections between the different categories because the focus was on the key topics themselves rather than on their connections.

Results

Description of Mind Maps on Classical Mechanics

29 mind maps on classical mechanics topics to be covered in physics teacher education were produced by the 29 study participants leading to a collection of 498 terms to be analyzed. On average, each expert included a total of 17.2 terms in their mind map. Table 1 provides an overview of the number of terms used by all subjects divided by the respective subject areas.

Table 1. Overview of the Number of Terms Used by Researchers to Prepare Their Mind Maps, Divided by the Experts' Research Fields (AP: Astrophysics, CM: Condensed matter, OP: Optics, TP: Theoretical Physics)

	# terms	# terms/participant
AP	116	19.3
CM	104	11.6
OP	39	13.0
TP	239	21.7

Frequency Analysis

As described in the data analysis section, a topic represented in the mind maps was identified as a key topic of classical mechanics for physics teacher education if and only if at least 20% of the participants included it in their mind map. This criterion was met by a total of 14 terms (see Figure 1). More than half of all respondents noted the *Newton's Axioms* (16 out of 29). Moreover, the *Equations of Motion*, the *Hamilton Formalism* (11 out of 29 each) and the *Lagrange Formalism* (10 out of 29) were included in most of the mind maps.

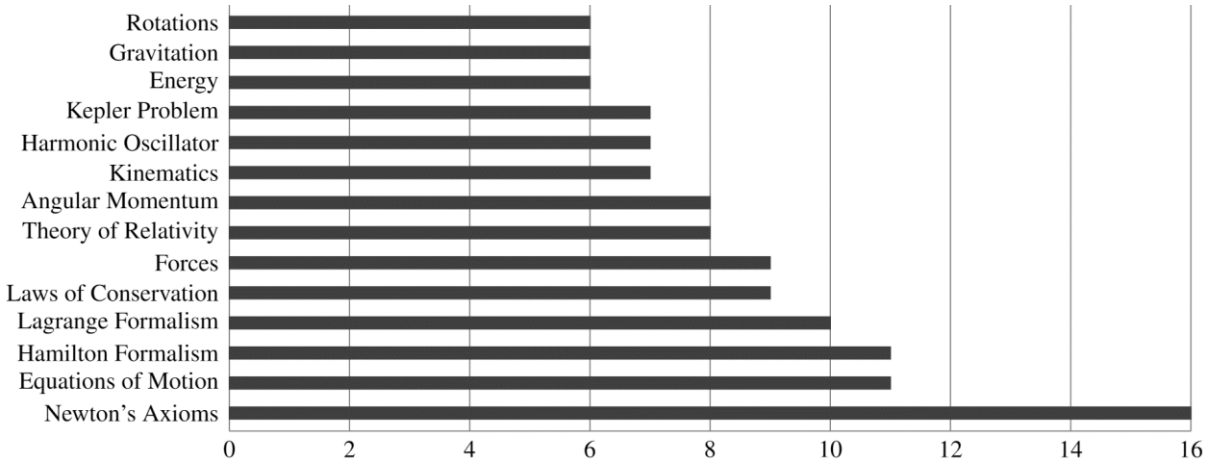

Figure 1. Overview of Key Topics of Classical Mechanics for Physics Teacher Education Identified from Experts' Mind Maps. The Number of Mind Maps Including Each Respective Topic Shown

Categorization

The mind map terms were categorized using an inductive procedure to identify foci in the perspective of researchers from the different disciplines. Figure 2 provides a graphical overview of the categories formed based on the mind map terms provided by the experts. The following categories are included in the coding manual:

- Category M1 (mathematical terms) includes all terms that specifically refer to mathematical content independent from physics, such as Poisson bracket or manifold.
- Category M2 (formalism of mechanics) comprises the five sub-categories kinematics and dynamics (anchor examples: free fall, inertia), coordinate systems (anchor examples: reference system, Galileo invariance), mechanical principles (anchor examples: D'Alembert's principle, stationary action principle), Theory of Relativity (anchor examples: Minkowski space-time, length contraction) and physical variables (anchor example: Hamiltonian).
- In category M3 (mechanical problems), mechanical problems are subsumed in six sub-categories oscillations (anchor examples: resonance, damped oscillation), rotations (anchor examples: Coriolis force, gyroscope), cosmology (anchor examples: planetary orbits, Kepler problem), friction (anchor examples: static friction, sliding friction), fluids and gases (anchor examples: Bernoulli equation, Magnus effect) and impacts (anchor examples: two-body problems, elastic impact).
- The fourth category M4 (applications and experiments) contains both, mechanics applications (anchor examples: vehicle construction, gears) and mechanics experiments (anchor examples: coupled pendulums, inclined plane).
- Category M5 (about mechanics) comprises the four sub-categories physicists (anchor examples: Newton, Lagrange), history (anchor examples: Aristotle's physics, theory of impetus), statements about mechanics (anchor examples: everyday-life, technology) and distinction from quantum physics (anchor examples: deterministic, macroscopic),
- The sixth category M6 (associations) consists of terms that are not characteristic for mechanics and is subdivided into the two sub-categories fields of physics (anchor examples: electrostatics, thermodynamics) and associative connections (anchor examples: phonons, Fraunhofer approximation).

Category M6 (*associations*) will not be included in the evaluation below due to comprising terms that cannot be associated with classical mechanics but rather address its periphery. This category consists of 20 different terms (46 mentions), which accounts for a share of 9.2% of all mechanics terms. Hence, five categories M1 to M5 have been subjected to further analysis.

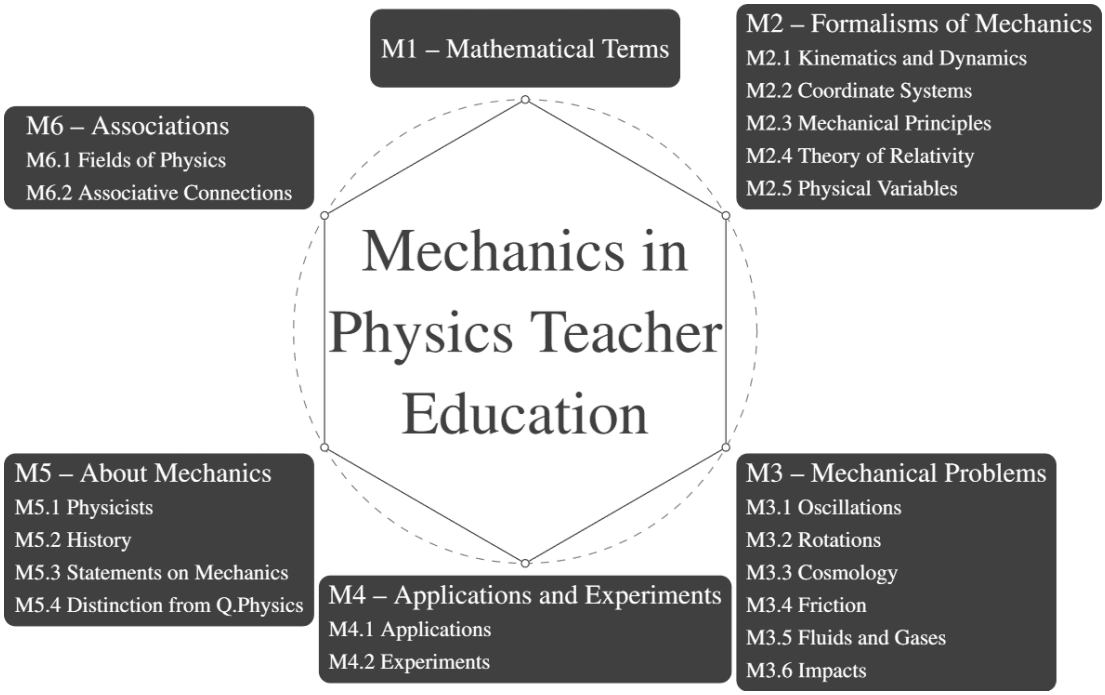

Figure 2. Category System Comprising Six Categories with Corresponding Sub-Categories: A Description of the Categories Including Anchor Examples Is Provided in the Body Text

Discipline-Specific Foci Regarding Classical Mechanics in Physics Teacher Education

To uncover whether different mechanics topics are given different priorities for physics teacher education by the representatives of the different physics disciplines, an extended frequency analysis was conducted. The results of this analysis are given in Table 2: In the column *Total*, the number of terms mentioned in the mind maps of the total sample is given for the individual (sub-)categories. The row $\sum$ provides the total number of terms included in the mind maps by the representatives of the respective physics disciplines (without category M6). For example, 60 of all mind map terms were assigned to the category *mathematical terms* (M1). Of these 60 terms assigned to category M1, 4 terms came from astrophysicists, 3 terms from condensed matter physicists, 10 terms from representatives from optics, and 43 terms from theoretical physicists. In Table 2, these frequencies are given in the column *# of terms*.

Table 2. Overview of the Results of the Frequency Analysis of the Terms Used in the Mind Maps on Mechanics per Category (see Figure 3) and by Physics Disciplines AP, CM, OP, and TP (See Table 1). A Description of the Row and Column Titles Is Provided in the Body Text.

	AP		CM		OP		TP		
Category	**# of terms**	**Relative frequency in [%]**	**# of terms**	**Relative frequency in [%]**	**# of terms**	**Relative frequency in [%]**	**# of terms**	**Relative frequency in [%]**	**Total**
M1	4	3.96	3	3.06	10	27.03	43	19.91	60
M2.1	15	14.85	27	27.55	6	16.22	45	20.83	93
M2.2	7	6.93	1	1.02	1	2.70	12	5.56	21
M2.3	7	6.93	4	4.08	2	5.41	11	5.09	24
M2.4	1	0.99	2	2.04	0	-	19	8.80	22
M2.5	16	15.84	14	14.29	1	2.70	24	11.11	55
M3.1	5	4.95	13	13.27	0	-	4	1.85	22
M3.2	11	10.89	7	7.14	0	-	9	4.17	27
M3.3	3	2.97	7	7.14	0	-	9	4.17	19
M3.4	3	2.97	0	-	2	5.41	6	2.78	11
M3.5	3	2.97	2	2.04	0	-	3	1.39	8
M3.6	7	6.93	1	1.02	0	-	1	0.46	9
M4.1	9	8.91	6	6.12	8	21.62	12	5.56	35
M4.2	4	3.96	4	4.08	0	-	5	2.31	13
M5.1	3	2.97	1	1.02	4	10.81	3	1.39	11
M5.2	0	-	5	5.10	1	2.70	0	-	6
M5.3	1	0.99	0	-	1	2.70	2	0.93	4
M5.4	2	1.98	1	1.02	1	2.70	8	3.70	12
∑	**101**	100	**98**	100	**37**	100	**216**	100	**452**

To uncover discipline-specific differences regarding classical mechanics key topics to be covered in physics teacher education, we suppressed the sub-categories in table 3, laying the focus on the representation of the different main categories as has been done by Winkler et al. (2021): A content-focus on topics from category Mx in the perspective of researchers from a specific discipline was identified if more than 15% of all terms in the mind maps of the respective experts could be assigned to category Mx.

Table 3. Percentage of Terms with Fit to the Respective Main Category out of the Total Number of All Terms that Respondents of a Subject Area Contributed to the Main Categories in %. Proportions above 15% are Written in Bold Face and are Used to Identify Content-Foci

Category	**AP**	**CM**	**OP**	**TP**	**Total number of terms**
M1	3.96%	3.06%	**27.03%**	**19.91**%	60
M2	**45.54%**	**48.98%**	**27.03%**	**51.39**%	215
M3	**31.68%**	**30.61%**	5.41%	14.81%	96
M4	12.87%	10.20%	**21.62%**	7.87%	48
M5	5.94%	7.14%	**18.92%**	6.02%	33
∑	100%	100%	100%	100%	**452**

It is striking that for the experts from optics and theoretical physics, a focus regarding classical mechanics topics to be covered in physics teacher education is on the category M1 comprising mathematical terms (OP: 27.03%, TP: 19.91%). In contrast, this category seems to hardly play a role according to the representatives from astrophysics and condensed matter (AP: 3.96%, CM: 3.06%). Conversely, we find a content focus regarding classical mechanics to be covered in physics teacher education on topics from category M3 comprising mechanical problems (AP: 31.68%, CM: 30.61%) among researchers from astrophysics and condensed matter, while the topics related to this category only plays a minor role according to researchers from optics and theoretical physics (OP: 5.41%, TP: 14.81%). For a graphical representation of these results see figure 3.

The above observation is underpinned by dividing the sample into two sub-groups, namely experimental (N = 18) and theoretical physics (N = 11), respectively: while it becomes obvious that both, experimental (44.07% of all mind map terms) and theoretical physicists (51.39% of all mind map terms), give priority to topics assigned to category M2 including the different formulations of mechanics (see table 4), there is a thematic focus on category M1 comprising mathematical terms (category M1) among the theoretical physicists (19.91% vs. 7.20% among experimental physicists) but on category M3 mechanical problems among experimental physicists (27.12% vs. 14.81% among theoretical physicists).

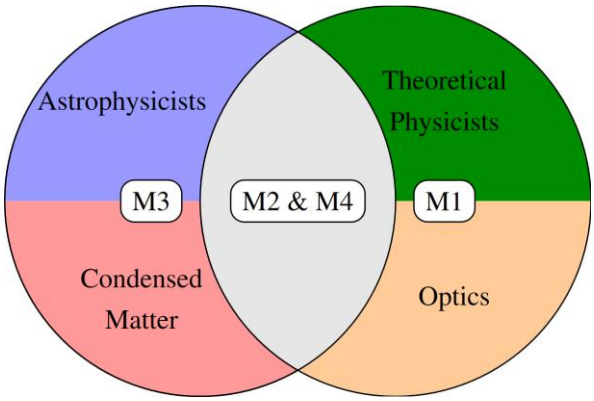

Figure 3. Analysis of the Experts' Mind Maps on Mechanics: Shared and Differentiated Foci Across Disciplines

Table 4. Percentage of Terms with Fit to the Respective Main Category out of the Total Number of All Terms Contributed by Respondents in Experimental or Theoretical Physics to Main Categories in % Proportions above 15% Are Written in Bold Face and Are Used to Identify Content Foci

Category	Experimental physics	Theoretical physics	Total number of terms
M1	7.20%	**19.91%**	60
M2	**44.07%**	**51.39%**	215
M3	**27.12%**	14.81%	96
M4	13.14%	7.87%	48
M5	8.47%	6.02%	33
∑	100%	100%	**452**

Discussion

The aim of the exploratory study reported in this article was twofold: On the one hand, we investigated which classical mechanics topics are regarded as essential for physics teacher education according to experts from different physics disciplines. On the other hand, we were interested in differences in content-foci regarding classical mechanics to be covered in physics teacher education across different physics disciplines.

In an author's earlier work, researchers' associations with quantum physics were explored – also using the mind map method and searching for differences among the experts' associations that can be traced back to their different subject-specific backgrounds (Winkler et al., 2021). In this study, the mind maps on quantum physics were found to be heterogeneous: That is, the experts' associations with quantum physics indeed strongly differed depending on the experts' research background. For example, the main associations of the scientists from theoretical physics and optics were grouped around the quantum formalism, while for researchers from astrophysics, the focus was rather on quantum effects or on their use in applications. Aspects that are related to fundamental principles of quantum physics were apparent in the associations of researchers across the different physics disciplines.

For the sake of comparison, in the study presented in this article, we asked the experts who had already participated in the above-mentioned study which classical mechanics concepts are most relevant in physics teacher education in their opinions. The study results indicate differences to the quantum realm: The mind maps on mechanics are rather homogeneous in terms of content as the categorization results show (see Table 3). In general, this provides evidence according to which there is a certain degree of consensus among physics experts from different disciplines as to which topics may be regarded as key topics for physics teacher education of classical mechanics. For example, a large proportion of all mind-map terms on mechanics could be assigned to the category M2 (mechanics formalism), across all disciplines: 45.54% of all astrophysicists' mind map terms belong to this category, and similar percentages are found for the participants from condensed matter (48.98%), optics (27.03%) and theoretical physics (51.39%). Hence, in the sense of Tseitlin and Galili (2005), the aspects assigned to this category can be regarded the nucleus of classical mechanics. Apart from this, the content focus for physics teacher education of classical mechanics seems to differ between experts only with respect to the corpus of classical mechanics in the sense of mechanics as a discipline-culture (Tseitlin & Galili, 2005). The participants from astrophysics and condensed matter placed a further content focus on the category mechanical problems (AP: 31.68%, CM: 30.61%), while for the participants from optics and theoretical physics, a stronger focus should be put on mathematical terms (OP: 27.03%, TP: 19.91%).

The findings of this study are consistent with the guidelines for high school physics programs published by the American Association of Physics Teachers (AAPT) in which – with regards to teacher preparation – it is stated that "physics teachers should be well grounded in physics content" (Cannon et al., 2002, p. 15): The AAPT recommends classical mechanics to be one of five major parts of physics teacher study programs and, in this respect, lays a focus on the concepts of force and motion – topics that are above all associated with category M2 (including subcategory M2.1

on kinematics and dynamics) in our study. Nearly 50% of the mind map terms collected in this study were dedicated to this category M2 and hence, indeed, our experts align with the AAPT recommendations in this respect. Similar comparisons hold true for guidelines for physics teacher programs in different countries across the globe.

Conclusion

Our mind map study identified Newton's Axioms, Equations of Motion, Hamilton Formalism, and Lagrange Formalism as key topics for classical mechanics in physics teacher education, according to 29 experts across different physics disciplines. Hence, we observed a consensus across groups regarding the relevance of the formalisms of mechanics. However, a further categorization of the mind map terms revealed that content foci in physics teacher education on classical mechanics differ between experts from different physics disciplines: Our results indicate that optics and theoretical physics experts focus more on mathematical aspects of classical mechanics, while astrophysics and condensed matter experts focus more on mechanical problems.

Recommendations

Organizing physics teacher education is a challenging task for physics faculties and departments at universities across the globe. Although the central role of classical mechanics in physics teacher education is undisputed, even in this context divergent interests and perspectives from different disciplinary cultures might exist when thinking about how to best support pre-service teachers' professional development. In this regard, the study presented in this article might help to communicate these different viewpoints among experts from different physics disciplines because our results indicate both, namely (a) differences, but also (b) the joint focal points. To describe the consensus among experts about classical mechanics key topics to be covered in physics teacher education in more detail, in further research – in particular, based upon the results presented in this article – using a Delphi study seems a sensible approach (Krijtenburg-Lewerissa et al., 2019).

Beyond classical mechanics as part of physics teacher education, the results of the study presented in this article recommend curriculum developers and lecturers to be aware of the fact that one's own view of what is at the core of teaching a given topic to a certain target audience is strongly influenced by one's own background and by how one is socialized. Hence, it seems relevant that curriculum developers and lecturers repeatedly put themselves in the shoes of colleagues with different subject-specific backgrounds – and in particular of their students – when it comes to refine curricula or to plan lecture or seminar series. In particular, this recommendation applies to the further development of study programs for physics teacher education, for example with regard to classical mechanics education in the context of the study entry phase. In further research, we will analyze as to how integrated courses, for example combining experimental with theoretical physics (Giesel & Strunk, 2022), might help to (a) allow for cross-fertilizations between the different disciplines, and to (b) support pre-service physics teachers' professional development.

Limitations

For the interpretation of this study's results, one needs to consider some limitations:

1. The small sample in our study is a limiting factor. In particular, the subject-specific analysis of the mind maps has only limited validity because different numbers of scientists from the four subject areas of astrophysics (6x), condensed matter (9x), optics (3x) and theoretical physics (11x) were involved. This means that individual persons' associations can lead to a distortion of the results, especially in the subject area of optics. To tackle these limitations, future research needs to include larger samples with a comparable number of experts from the different physics disciplines.
2. In this study, we have analyzed the terms used by the experts to create their mind maps around the overarching theme of classical mechanics as a part of physics teacher education. It is noteworthy that we did not consider different interpretations that the experts assign to the respective terms. For example, using the term differential equation different experts might have different concrete aspects in their minds, both in terms of content and in terms of depth. We argue that future research employing qualitative methods might substantiate the findings of this study in this regard.
3. Third, we used the mind map method in this study to naturally stimulate the experts' in thinking about classical mechanics key concepts for physics teacher education without (a) influencing their opinions or (b) awaking ad hoc associations during study participation which do not reflect the experts' own priorities. Hence, in light of our research questions, we were not interested in the connections between the terms used by the experts for the mind map creation. However, we believe that considering the connections between the terms and differences in this regard might provide deeper insights into the dependence of physics researchers' opinions on what really matters when it comes to teaching classical mechanics to pre-service teachers. Therefore, it might be useful to ask participants to create Concept Maps (see Bizimana et al., 2022; Kinchin et al., 2019).

4. To avoid influencing the participants, we did not specify whether to prepare mind maps including key topics for experimental or theoretical physics courses as part of physics teacher education. Nonetheless, it is possible (and likely) that the experts had a specific course in mind while creating the mind maps.

Authorship Contribution Statement

Winkler: Concept and design, data acquisition, data analysis, drafting manuscript, final approval. Veith: Visualization, critical revision of manuscript, final approval. Bitzenbauer: Concept and design, critical revision of manuscript, final approval, supervision.

Ethics Statement

Ethical review and approval were waived for this study due to the fact that the study was in accordance with the Local Legislation and Institutional Requirements. Informed consent was obtained from all participants.

Conflict of Interest

No conflicts of interest to be declared.

Funding

This research was funded by the Open Access Publishing Fund of Leipzig University supported by the German Research Foundation within the program Open Access Publication Funding.

References

Baumert, J., Kunter, M., Blum, W., Brunner, M., Voss, T., Jordan, A., Klusmann, U., Krauss, S., Neubrand, M., & Tsai, Y.-M. (2010). Teachers' mathematical knowledge, cognitive activation in the classroom, and student progress. *American Education Research Journal*, *47*(1), 133-180. https://doi.org/10.3102/0002831209345157

Bizimana, E., Mutangana, D., & Mwesigye, A. (2022). Fostering students' retention in photosynthesis using concept mapping and cooperative mastery learning instructional strategies. *European Journal of Educational Research*, *11*(1), 103-116. https://doi.org/10.12973/eu-jer.11.1.107

Buzan, T., & Abbott, S. (2017). *Das mind-map buch* [The mind-map book]. Mvgverlag.

Callahan, P., Cannon, B., Chesick, E., Mackin, J., Mandel, S., & Wenning, C. (2009). *The role, education, qualifications, and professional development of secondary school physics teachers*. The American Association of Physics Teachers. https://tinyurl.com/3zpvcea7

Cannon, B. T., Ewald, G., Ezrailson, C., Nelson, J., Rice, R., Schmidt, J. Secrest, R., & Winborne, A. (2002). *Guidelines for high school physics programs.* The American Association of Physics Teachers. https://tinyurl.com/45hbw87v

Carson, R., & Rowlands, S. (2005). Mechanics as the logical point of entry for the enculturation into scientific thinking. *Science & Education*, *14*, 473–493. https://doi.org/10.1007/s11191-004-1791-9

Champagne, A. B., Klopfer, L. E., & Anderson, J. H. (1980). Factors influencing the learning of classical mechanics. *American Journal of Physics*, *48*(12), 1074-1079. https://doi.org/10.1119/1.12290

Crowe, M., & Sheppard, L. (2012). Mind mapping research methods. *Quality & Quantity*, *46*, 1493-1504. https://doi.org/10.1007/s11135-011-9463-8

de Winter, J., & Airey, J. (2022). Pre-service physics teachers' developing views on the role of mathematics in the teaching and learning of physics. *Physics Education*, *57*, Article 065007. https://doi.org/10.1088/1361-6552/ac8138

Friege, G., & Lind, G. (2004). Leistungsmessung im leistungskurs [Performance measurement in advanced courses]. *Der Mathematische und Naturwissenschaftliche Unterricht – MNU*, *57*, 259-265.

Galili, I. (1995). Mechanics background influences students' conceptions in electromagnetism. *International Journal of Science Education*, *17*(3), 371-387. https://doi.org/10.1080/0950069950170308

Galili, I., & Goren, E. (2022). Summary lecture as a delay organizer of cultural content knowledge. *Science & Education*. Advance online publication. https://doi.org/10.1007/s11191-022-00348-w

Giesel, K., & Strunk, C. (2022). *The elite graduate programme.* FAU. https://www.physics-advanced.de/

Hestenes, D., Wells, M., & Swackhamer, G. (1992). Force concept inventory. *The Physics Teacher*, *30*(3), 141-158. https://doi.org/10.1119/1.2343497

Kinchin, I. M., Möllits, A., & Reiska, P. (2019). Uncovering types of knowledge in concept maps. *Education Sciences*, *9*(2), Article 131. https://doi.org/10.3390/educsci9020131

Krijtenburg-Lewerissa, K., Pol, H. J., Brinkman, A., & van Joolingen, W. R. (2019). Key topics for quantum mechanics at secondary schools: A Delphi study into expert opinions. *International Journal of Science Education*, *41*(3), 349-366. https://doi.org/10.1080/09500693.2018.1550273

McKagan, S. B., Perkins, K. K., & Wieman, C. E. (2010). Design and validation of the quantum mechanics conceptual survey. *Physical Review Special Topics – Physics Education Research*, *6*(2), Article 020121. https://doi.org/10.1103/PhysRevSTPER.6.020121

Shulman, L. (1987). Knowledge and teaching: Foundation of the new reform. *Harvard Educational Review*, *57*(1), 1–22. https://doi.org/10.17763/haer.57.1.j463w79r56455411

Tseitlin, M., & Galili, I. (2005). Physics teaching in the search for its self. *Science & Education*, *14*, 235-261. https://doi.org/10.1007/s11191-004-7943-0

Winkler, B., Bitzenbauer, P., & Meyn, J.-P. (2021). Quantum physics ≠ quantum physics. A survey of researchers' associations. *Physics Education, 56*(6), Article 065031. https://doi.org/10.1088/1361-6552/ac28df