

Cognitive dimensions in students' mental models of linear light polarization

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Learners often struggle to develop expandable mental models of polarization due to its abstract nature and the multitude of models used to describe it. A closer examination of the structure of mental models for linear polarization is therefore worthwhile in order to gain insight into mental abstraction processes. Existing research has largely documented misconceptions, leaving the underlying cognitive structures of mental models insufficiently explored. To address this gap, we employed the Fidelities Model of Conceptual Development (FMCD) to investigate learners' cognitions of linear polarization. The framework, distinguishes two dimensions of students' mental models: Gestalt, which refers to visual and structural representations, and Functionality, which captures how well a model explains underlying processes. The degrees to which these dimensions align with reality allow for a typification of learners' reasoning patterns. We developed a test instrument based on established students' mental models and validated it through expert review and think-aloud studies. In a cross-sectional survey with $N = 178$ German secondary school and university students, confirmatory factor analysis confirmed a robust two-factor structure (CFI = 0.96, RMSEA = 0.03, SRMR = 0.07) with solid factor-reliability ($\omega_{FF} = 0.71$, $\omega_{FG} = 0.81$). Descriptive results showed developmental trends: while secondary students often exhibited “dual” models combining both FG and FF, university students increasingly relied on functionally oriented reasoning. The findings validate the FMCD in the domain of polarization and provide a diagnostic tool that informs instructional design for supporting students' conceptual development in optics.

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I. INTRODUCTION

Abstractness, as defined by Mason and Just, suggests “some separation from perceptual and motor representations and the daily activities and thoughts that human beings have engaged in for millennia” [1] (p. 905). Since polarization is mostly inaccessible to direct sensory experience, with liminal phenomena like Haidinger's brushes, as well as being theoretically challenging [2–4], it serves as a paradigmatic example of an abstract physical concept. From a constructivist perspective, every learning process, particularly within abstract topics, results in an individual cognitive equivalent of the scientific models within each learner's mental framework. Bridging formal physics models and learners' understanding involves a process of cognitive reconstruction, wherein a mental model serves as a subjective representation [cf. [5]]. The term mental model is understood as a cognitive representation that enables an individual to understand the functioning of

complex systems [cf. [6]]. Similarly, Ubben and Heusler describe mental models as “depictions and meanings our mind gives to phenomena and their underlying structures” [5] (p. 1349) drawing on the earlier discussion by Rickheit and Sichelschmidt [7]. For educators, especially abstraction processes are difficult to moderate [8–10], and thus deciphering the inner workings of students' mental models is of great interest. In order to investigate the developmental processes of learners' mental models, their underlying structures must be considered. A potential framework describing this development was proposed by Ubben and Heusler and later by Ubben and Bitzenbauer in the *Fidelities Model of Conceptual Development* (FMCD) [5,11]. This framework was empirically found and validated in the domains of atomic physics [5] and quantum mechanics [11], and its usefulness has also been demonstrated in various other contexts [12–14]. Specifically, in the context of quantum mechanics, the described mental models encompassed beliefs about the photon. Photons are usually described by various quantum states [13,15]: Among others, polarization states are part of the possible characterizations. Even though polarization is “a fully classical concept, a single photon can be assigned polarization states in the quantum realm” [13] (p. 4). Due to this contextual proximity, it stands to reason to employ the

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Fidelities Model of Conceptual Development within the topic of light polarization as well in order to gain insight into the structure of learners' mental models in this field. Despite numerous studies on students' mental models of linear light polarization in the form of mere statements like the works from Ambrose *et al.* [3], Cvenic *et al.* [16], or Aykutlu *et al.* [17], there is still no empirically validated model for the categorical diagnosis of different mental representations in this specific domain. Therefore, in this context, an instrument that operationalizes students' mental models within the fidelities framework was developed. We will use this instrument further to demonstrate how mental models can be described from the perspective of the fidelities model. Thus, we investigate the following research questions.

II. RESEARCH QUESTIONS

1. Does a two-factor structure as proposed by the Fidelities Model of Conceptual Development, characterized by *Functional Fidelity (FF)* and *Fidelity of Gestalt (FG)*, also appear in learners' mental models on linear light polarization?
2. According to the *Fidelities Model of Conceptual Development*, what types of mental models can be observed with learners surrounding linear polarization?

III. RESEARCH BACKGROUND

In the following section, we provide some insight into the considerations that went into the development of a suitable instrument, as well as the scientific backdrop this work benefits from. To start with, we give an overview of prevalent mental models of linear light polarization. Following this, the *Fidelities Model of Conceptual Development* is introduced to familiarize the reader with the theoretical grounding.

A. Learners' mental models of linear light polarization

The most often reported mental models in the literature spanning from high school to university settings are either predicated by a missing understanding of the interdependence of the electric and magnetic field [16–21], surround the connection to the physical quantity “intensity of light” [16,17,19,22] or base themselves on attempts at explanation through pictures [3,17,23] as visible in Table I.

Those mental models can range from a separation of the electric and magnetic field to not arguing in the field or wave model at all and instead attributing properties of geometrical optics [3,17,26]. Common depictions like the rope-wave analogy to explain the transmission axis of a polarizer can be misinterpreted and lead to struggles with connecting the conventional 2D representation of an electromagnetic wave with the polarizing effect. Instead

TABLE I. Overview of prevalent student mental models of linear light polarization as documented in the researched literature. The statements summarize recurring reasoning patterns and misconceptions, spanning contexts from high school to university instruction. References identify the studies in which each mental model was reported.

Mental model	Literature
Either the electric or magnetic component of the field is transmitted through a polarizer and only if that component is parallel to the transmission axis of the polarizer.	[16–21]
Polarizing filters dim the light, because the filter only transmits some of the light. It is acting as a kind of gray filter. The experiment determines the applied explanatory model, for example for diffraction of polarization one must use the wave model and for the photoelectric effect the particle model	[16,17,19,22] [24]
Polarizers consist of molecule chains, which act like a slit or grating and polarization can be compared to a parallel oscillating rope-wave fitting through said grating.	[3,17,23]
Unpolarized light has all possible polarization states or none.	[25]
Propagation direction and oscillation direction of light are the same.	[3,17]
Light is a beam and therefore we cannot attribute polarization as a two-dimensional vector to light.	[17,26]
Since a polarizer can have any orientation, the orientation of the polarizer determines the polarization state, thus it does not make sense to speak of “two-state systems” with linear polarization of photons.	[26]
A single slit is a polarizer.	[17,18]
Polarizers do not affect the EM wave at all.	[17]
Polarized light propagates in only one direction. In polarized light, the electric field propagates in only one direction	[3,17]
Polarization leaves light distributed more properly.	[17]
Hybrid models of light are applied or models mixed up for explanations.	[17]
Light loses its magnetic field as it polarizes.	[3]
The magnetic field is absorbed as it polarizes.	[3]
Most of the incoming light beams collect in one direction as light polarizes.	[3]
(Sound) waves can be polarizes by collecting them into a single wave.	[3]
Polarizers are filters that only allow beams propagating in a certain direction to pass.	[3]
Polarizers are refractive mediums that collect light in a certain direction.	[3]

of viewing linear polarization as the restriction of the electric field to a single axis, learners often fail to apply the spatial characteristics of the wave model [16,18,27]. Such difficulties eventually lead to descriptions like “if one grating is like this [parallel to the direction of wave oscillation] or at some angle, the wave can pass through it. The other is like this [perpendicular to the first] and the wave cannot pass through” [17] (p. 6), where the polarizer seems to be viewed like a grid, blocking waves that do not align perfectly with it. Another problem seems to be in how polarized light is obtained and later interpreted: Students are often confused about the origin of (linear) polarization as well as its implications on surrounding optical topics [3,22,26]. Those mental models include confusing the direction of electric field oscillation with wave propagation, assuming no interaction between the field and the polarizer at all, and believing that a polarizer transmits light oscillating parallel to its bars on the basis of said grid analogy [cf. [3,17]]. In connected topics like interference or intensity, similar problems arise [28]: Students who conceptualize polarizers as simply “blocking” light tend to interpret polarization primarily as a process of intensity reduction. This view is reflected in statements like “polarization is only [...] a process of decreasing the intensity of light” [17] (p. 8) or “polarizing glasses and polarizers [...] filter light” [17] (p. 10). Additionally, when studying technical applications of light polarization like displays or sunglasses, students also confuse the property of color (more specifically, wavelength) with polarization [16–18]. In light of these multifaceted variations of mental models, Aykutlu *et al.*, proposed a categorization into the subcategories of “confusing electric field oscillation direction” and “[problems with] the function of polarizers” [cf. [3]]. However, Singh and Marshman already identified further consequences within learners’ mental models in 2015 with regard to more advanced topics such as quantum physics, where the photon model must ultimately be used [cf. [26]]. This is clearly illustrated by argumentation structures such as “Since a polarizer can have any orientation, the orientation of the polarizer determines the polarization state, thus it does not make sense to speak of ‘two-state systems’ with linear polarization of photons,” whereby classical model interpretations were transferred to quantum mechanical processes [cf. [26] (p. 5)]. The varied mental models and their accompanying problems mirror the fact that light polarization does not lend itself to a single, directly accessible description. Rather, as in many areas of modern physics including quantum phenomena, it is captured and described by multiple physical models, the application of which is expressly contextual [cf. [29,30]]. The plurality of models requires learners to distinguish between the various functional roles each model serves in understanding phenomena. This inherent plurality poses a difficulty for learners, who must navigate when and how to apply each model, as the choice of explanatory frameworks

is often determined by the experimental context [cf. [24]]. Challenges in distinguishing explanatory analogies from physical models have been argued to underlie persistent difficulties in students’ understanding of polarization [17]. In addition, metacognitive knowledge about which representations to choose is key in physics learning, since learners must recognize both the functional purposes and the visual forms of representations that are valued in each situation [cf. [9,10]]. While prior research has documented mental models in the form of statements so far, what remains lacking is a systematic framework that captures their structural characteristics as well as their functional and visual dimensions—a gap that the fidelities model directly addresses.

B. Fidelities Model of Conceptual Development

For the purposes of this analysis, we adopt the theoretical approach proposed by Ubben and Bitzenbauer [11] for a more precise examination of mental models. Thus, mental models can have:

- ... visual or bodily aspects—called *Gestalt*, which are often bound to sensory modalities.
- ... functional, abstract aspects—called *Functionality*, which represent experiences or observations in terms of their function and operational role.
- ... individual aspects, which build upon biographical events. From a constructivist learning perspective, this aspect primarily encompasses the individual learning process, which depends on experience and personality. This characteristic therefore gives mental models temporal fluctuation—mental models are considered to be variable in abstraction or scope.

This particular factorial structure is also reflected in research on neural processes within cognitive psychology. For example, Mason and Just identify four cognitive factors involved in physics learning: visualization of motion, energy flow, periodicity, and algebraic forms. They, too, “suggest that there is a common path from the basic capabilities of the human brain to the abstract physics concepts” [1] (p. 910). While the work of Mason and Just “suggests speculative descriptions of knowledge types and information codes [of physics schooling] [...] grounded in the brain systems that represent the physical world [[1] (p. 912)], their findings also reflect the underlying results of previous studies (i.e., periodicity is always linked to a mathematical understanding and thus function) hinting at two-dimensional structures in mental models [cf. [11,31,32]].

Based on these considerations, Ubben and Bitzenbauer, proposed the *Fidelities Model of Conceptual Development* as a tool for investigating said mental models [5,11]. The framework derives the following dimensions based on the properties of mental models:

- *Fidelity of Gestalt (FG)*, which describes that one can understand their mental models “as exact visual

presentations of phenomena or exact depictions of how things look” and “how much the mental models’ Gestalt is perceived as accurate” [11] (p. 2).

- *Functional Fidelity (FF)*, which describes that one can understand their mental models as “appropriate descriptions of how phenomena work” and “how much the mental models’ underlying abstract functionality [...] is perceived as accurate” [11] (p. 2).

For example, in the context of light polarization, a typical sense of *Gestalt* would be the analogy between the mechanical oscillation wave of a rope and a light wave. A high degree of Fidelity of Gestalt in students’ mental model means corporeal properties of the mechanical rope-wave are directly translated into the students’ mental model of light waves, i.e., potentially creating misconceptions like a polarizer working like a grid by only letting parallel oscillation pass (see Sec. I). In contrast, for the *function* of absorption, an exemplary reasoning with a high degree of *functional Fidelity* would refer to the interaction of the electromagnetic wave with the bound electrons in the polarizer’s material. These electrons can be driven into oscillation along certain directions, which leads to selective absorption of the corresponding field components and thus to polarization. These factors, together with empirical findings and widely recognized student conceptions, define a typology of mental models that can be characterized by archetypical combinations of the two underlying dimensions (as shown in Fig. 1):

1. Nondeveloped type (low manifestation of FG, low manifestation of FF).

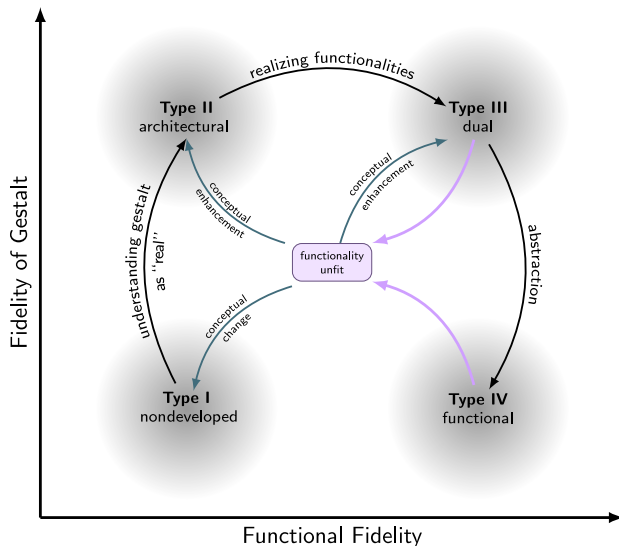


FIG. 1. Fidelities Model of Conceptual Development: From understanding a certain Gestalt as “real” over accessing the functionalities to abstracting understanding of a model is developed. Understanding develops further in an iterative process: Is a given model not applicable anymore, for example, due to lack of precision, it has to change or evolve [14] (p. 17).

2. Architectural type (high manifestation of FG, low manifestation of FF).
3. Dual type (high manifestation of FG, high manifestation of FF).
4. Functional type (low manifestation of FG, high manifestation of FF).

While learners of the nondeveloped type still only show the ability to recite declarative knowledge, the architectural type is already showing understanding by consulting primarily the *Gestalt* of a concept within their reasoning. The third type, which is called “dual understanding” appears to combine both *Functionality* and *Gestalt* in a way: Learners displaying this kind of mental models often view their representations as “scaled up or down replica[s]” [14] (p. 13).

Finally, the fourth type exhibits a high manifestation of *Functional Fidelity* attended by low *Fidelity of Gestalt*. The *Gestalt* of models or concepts is not at the forefront of their thinking anymore and instead “is only seen as a carrier [...] for the processes encapsulated in the idea” [14] (p. 13). The transition between those types of understanding is fostered by conceptual change or rather enhancement, scaffolding students’ conceptions step by step in a constructive genesis. Figure 1 shows this mechanism with the interdependent circlet named “functionality unfit”: Mental models and subsequently their interpretations are constructively changed and evolved when their Functionality and appliance does not fit a student’s reality anymore [cf. [14]]. Therefore, any learning process gained by an evolution of a mental model and its interpretation also governs the abstraction process and the development between the described “types” in the FMCD. The model goes along with classical constructive concept development theory, but deals with mental models and their interpretation and transfer to reality on a metalevel by considering the dimensions Fidelity of Gestalt and Functional Fidelity. For example, a person placed along the dimensions in the dual type (III) may use the analogy between the mechanical oscillation wave of a rope and a light wave in a functional-mathematical as well as quite literal-graphic way to explain the structure of a wire-grid polarizer. But only when the visual aspects of this mental model are failing them, e. g., the law of Malus does not align with their view of how a light wave passes a polarizer, the mental model is questioned and enhanced by changing the functional aspect of the rope-wave analogy to attributing the transitional axis to the “passing” of the wave and connecting a mathematical projection to the “how” this passing is achieved. In this enhancement/change, the Gestalt of this mental model loses importance in the explanation and thus the Fidelity of Gestalt reduces, the abstraction gains.

IV. INSTRUMENT DEVELOPMENT

As mentioned earlier, part of this research is to create a fitting test instrument for assessing the underlying structure

of mental models on linear light polarization. This section will give an overview of the developmental and evaluation process of said instrument. In combination with the empirical evaluation, this process will lend an insight into the suitability of the instrument to dissecting students' mental models of linear polarization of light. This captures the first research question and thus is conducive to the reliability and validity of the described research. The aim of the instrument is to capture the underlying structures of mental models. The focus is not on detecting technically correct or incorrect concepts, but rather on activating different mental models and, in a second step, capturing the way in which these models are interpreted. The mental models collected are operationalized along the dimensions of Functional Fidelity (FF) and Fidelity of Gestalt (FG). Accordingly, the items are formulated in such a way that they represent mental models, but their linguistic design contains an inherent emphasis on either Gestalt or functional aspects. In this way, it is not the existence of a particular mental model *per se* that is captured, but rather the interpretation of one's own mental model along the two fidelity dimensions. As a result, the scales consist of statements that correspond to typical student responses and thus reflect authentic mental models, but are not answered on a technical correctness dimension. Instead, the students indicate their agreement with the individual statements on a rating scale. Agreement with an item that corresponds to a particular mental model can thus be interpreted as an indicator of the strength of the respective dimension (FF or FG). The full final scales can be found in the Appendix.

A. Target group

As previously described, this research aims to operationalize FF and FG in the context of students' mental models on linear light polarization. Our intended population includes upper-secondary students (roughly equivalent to grade 10 and higher in the German school system) and beginning university students.

B. Domain description, item development, and question format

In order to capture mental models along the two dimensions proposed in the fidelities framework, Functional Fidelity (FF), and Fidelity of Gestalt (FG), we adopted typical statements of students' conceptions from the aforementioned literature [17] and adjusted them such that agreement could be interpreted as indicative of either Gestalt-oriented or function-oriented reasoning. To ensure the content validity of the instrument at an early stage of development, a widespread method is to prepare a blueprint of the underlying subtopic-structures prior to actively formulating statements [33]. We adopted this method, determining content domains based on the sources described in Sec. III A, which are described in the

following. As a "well-constructed test blueprint, also referred to as a table of item specifications, provides the necessary structure to foster validity" [33] (p. 8), the extractions from the literature were chosen such that they could be associated with at least one aspect of this table. Association with each subdomain of linear polarization was noted by the binary rating 1 for yes and 0 for no. An overview table was ultimately revised so that all cells were filled with positive values. Specifically, the content domains comprise the following distinct, but not exclusive, seven aspects:

- Measurement of polarization: Understanding polarization through experimental setups, instruments (e.g., polarizers), and causal relationships directly related to measurement. This includes how polarization states can be identified, compared, or quantified via observable effects such as changes in intensity [17]. Items assigned to this category focus heavily on technical aspects.
- Detection or perception of polarization: Visual perception and interpretation of polarization effects, for example through intensity changes when looking through filters, Haidinger's brushes, or polarization-sensitive materials [13]. Complementing and contrasting with the category "measurement," items in this category include aspects that deal with the observation and perception of the impacts and effects of polarization.
- Polarization as a physical quantity: Conceptions of polarization as an independent, describable property in physics that is measurable, changeable, and quantifiable.
- Polarization as a property of waves: Understanding polarization as a direct consequence of the wavelike nature of light [16,18,27].
- Polarization as a property of light: Conceptions of polarization as a fundamental property of light as an electromagnetic wave, independent of other properties such as wavelength, intensity, or propagation direction [cf. [17]].
- Applications of polarization: Everyday or technical applications, for instance in photography, sunglasses, LCD screens, or stress analysis in materials, emphasizing the relevance of polarization beyond the classroom.

In extracting usable items from the presented literature, the goal is not to sharply delineate its various facets and assign them precisely to one or more areas, but rather to validate the physical phenomenon of "polarization of light" in its holistic entirety. The distribution of the content domains with the number of allocated items is shown in Table II.

The items were designed so learners can either agree or disagree with the statements on a four-point rating scale. Agreement is meant to indicate Gestaltlike or Functional thinking, hence the answer format was selected as a

TABLE II. Distribution of developed items across the content domains during different stages of the study. FF, number of items on the Functional Fidelity scale corresponding to the subdomain vs FG, number of items on the Fidelity of Gestalt scale corresponding to the subdomain. The domains are origin of polarization, measurement of polarization, perception of polarization, polarization as a physical quantity, polarization as a property of waves, polarization as a property of light, and applications. Said domains are explicitly explained in Sec. IV B.

FF/FG timeline	Origin	Measurement	Perception	Physical quantity	Property of waves	Property of light	Applications
Before evaluation	10/10	6/4	13/13	13/5	12/9	11/10	3/4
Before CFA	9/10	4/4	10/13	10/5	10/9	11/11	3/3
Final	4/5	3/3	4/7	7/2	7/3	8/4	1/1

graduated agreement scale combined with numerical representations. The options ranged from “I do not agree at all” (=1) to “I completely agree” (=4). It is important to emphasize that the items in the instrument are not intended to represent physical concepts in the sense of clearly defined expert-level knowledge. Instead, the items are formulated as plausible but individual ideas of the pupils, reflecting how learners can describe or interpret phenomena related to the linear polarization of light in natural language. The purpose of the instrument is therefore not to assess whether students have specific conceptual knowledge, but to examine how students interpret such statements and which underlying structures of their mental models are activated in the process. Accordingly, the use of a concordance-based rating scale is intended. By asking students to indicate the extent to which they agree or disagree with a particular statement, the instrument captures students’ interpretations of these statements rather than their ability to reproduce canonical explanations. In this sense, the instrument explicitly allows for, and indeed relies on, a certain degree of interpretative freedom. This interpretative openness is not a limitation of the design, but a central feature of what the instrument is intended to measure: cognitive dimensions of mental models rather than fixed conceptual entities. The wording of the items reflects a conscious compromise. The items represent a compromise between intelligible wording, coverage of the seven identified content aspects, and natural language, while maintaining accuracy to a certain extent case by case. In particular, the use of natural language and a limited degree of linguistic ambiguity have been retained in order not to steer students toward specific expert interpretations and to preserve the authenticity of students’ thinking. To give an example, item F06, in its final state after think-aloud study and expert revision, was worded as “a polarizer influences both the intensity of the light and the direction of oscillation of the electromagnetic wave.” The aim of the item is not to require a complete description of the physical process, but to determine whether the interpretation of the statement activates a functional idea of interaction or projection. Agreement with this item can therefore be interpreted as indicative of Functional Fidelity, insofar as the polarizer is understood as an element that influences both the intensity and a directional property of the wave.

If a professionally differentiated mental model is activated in the process, this typically includes a projection-based idea, but this is also deliberately not explicitly queried. An explicit specification of the incident polarization state was deliberately avoided, as such a specification would limit the learners’ scope for interpretation and draw attention to technical constraints that are not the focus of the intended survey. This design decision is consistent with the goal of capturing mental models as they are expressed and interpreted by learners, rather than as they would be articulated under strictly limited formulations prescribed by experts. This initial iteration of the development rendered a total of 54 items, which were subsequently introduced into the evaluation process.

C. Evaluation of the instrument

The instrument underwent several evaluations as illustrated in Fig. 2. After revising the items extracted from the literature within the group of authors, the instrument was introduced into an expert survey and a think-aloud study. The revision after those instances yielded 49 items. Those revised items were then given into the later explained cross-sectional survey for a confirmatory factor analysis (see Sec. VA), which then rendered a final set of 22 items for the test instrument. The details of the expert survey and think-aloud study themselves are explained below.

1. Expert survey

The expert survey was conducted digitally via LimeSurvey with nine experts of higher physics education with affinity to quantum sciences and optics from varying universities in Germany. In the survey, we analyzed the items from two perspectives: On one hand, we asked to what extent the agreement with the items may be regarded as indicative of Gestalt and Functional thinking, respectively. On the other hand, we aimed to identify options for improvement of the items in terms of language or missing content. As for the first part, we asked the experts to rate on a dichotomous scale, whether they agree or disagree with the item being assigned to represent the latent construct (Gestalt or Functional thinking) and present a justification of their answer. We found that the experts showed overall consensus on their agreement with our selection and found

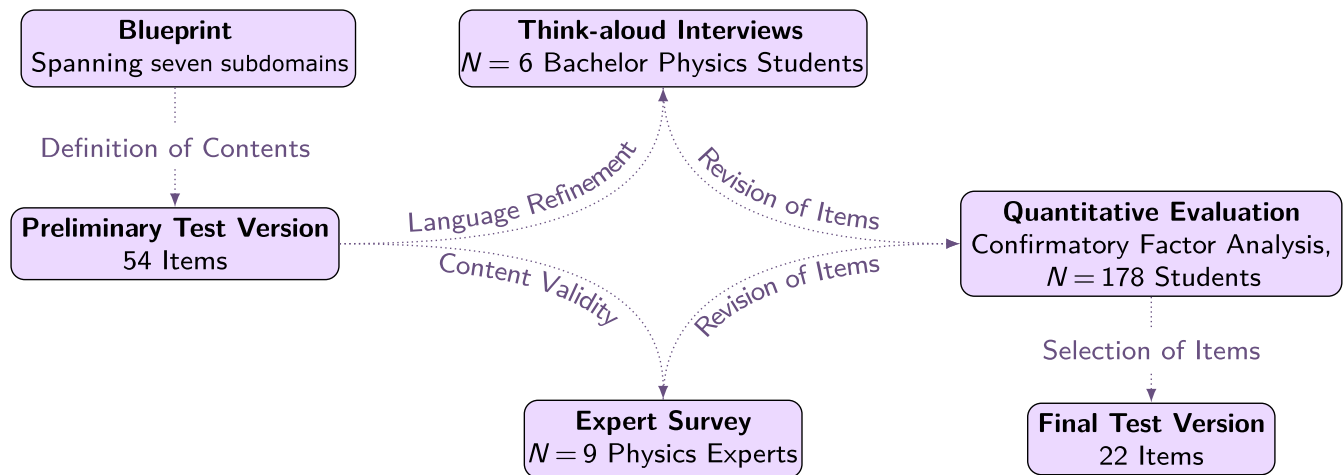


FIG. 2. Flowchart on the development process of the test instrument for the fidelities model on linear polarization.

no particularly important content aspects of linear polarization unrepresented.

Hence further analysis of the expert feedback focused on detail specification and language refinement with regard to wording, spelling, grammar, as well as technical language. In the following, we provide examples as to how some items were reconstructed according to the mentioned aspects. Several wording adjustments were implemented. For example, item F07 on the FF scale was revised from “through the combination of multiple polarizers” to “through one or the combination of multiple polarizers” in order to increase precision and to avoid suggesting that only more than one polarizer can be used to deliberately alter the polarization of light. Also the feedback to “stay with certain descriptions without presupposing certain views” led to changes in terminological choices. Here consistency was ensured by always using the term polarizer. Expressions such as “polarizing filter” (original: Polfilter) or “ $\lambda/4$ -plate” (original: Lambda-Viertel-Plättchen) were deliberately avoided, since they could evoke specific mental models, for example, interpreting the polarizer merely as a filter that blocks light, as previously described. Simple revisions like deleting quotation marks so as not to influence students’ decisions fall under the aspect of spelling. The invaluable insight of the experts greatly sharpened the presented items while preserving and deepening the content.

2. Think-aloud study

The think-aloud study was conducted with six university physics-bachelor and physics-teacher students prior to higher optics education. The fact that students were at the university level before taking their higher-level optics courses provides a reasonable basis to ensure that their language and knowledge of physical terminology closely coincide with that of high school students. The revised

items were additionally audited and examined for comprehensibility, language, and concision in a think-aloud study with six physics students in detailed one-on-one interviews examining the questions:

- Is the item comprehensible particularly in terms of terminology?
- According to your understanding of the item, how would you answer?
- Are there improvements to be made?

Within the think-aloud study the students were asked to voice all thoughts while processing the items consecutively. In cases of unclear accounts, follow-up questions were asked and the students also had the option to visualize their thoughts with pen and paper. This shed light on ambiguous or unclear items, imprecise or typically unknown wording, association and potential interpretations as well as the question whether the items were understood as intended. A few examples of the resulting revisions are as follows:

- Revisions in terms of concision: Terms like “how much light” were changed to—in the case of item F07 of the FF scale (revised)—“what intensity is measurable.”
- Sharpening wording: For example, in item G10, “relative to each other” was added, because only speaking of rotating two polarizers did not specify the imagined setup clearly enough, causing the students to additionally explore multiple setups and compare results.
- Changes due to association or interpretation: The item from the FG scale (unrevised) “Light rays that strike a polarizer at an angle are completely blocked,” which triggered the ray model as well as the quite undefined term of “at an angle,” was specified into two items by adding “relative to the polarizer axis” and “relative to the beam path” into it. Which resulted in the remaining item of G02 “Light that hits a polarizer at an angle to the polarizer axis is completely blocked.”

- The linguistic revisions included, for example, the use of the commonly known term “polarizer” instead of “polarizing filter” in order to avoid triggering confusing or contradictory mental models.

Those evaluation results contributed greatly to ascertaining construct and content validity. To preserve content validity even after revision, the coverage of the subtopics in the blueprint (cf. Table II) was consulted once more, before proceeding with further testing. The consultation showed that, despite the item reduction, the coverage of the defined content domains remained intact. Each domain retained representation on both scales, thereby preserving content validity.

V. METHODOLOGY

A. Study design and sample

We conducted a cross-sectional survey to explore learners’ mental models of linear polarization. The instrument was designed to capture the full range of model development; however, no instructional intervention was implemented as part of this study prior to test administration. The learners received no additional instruction on polarization beyond their regular coursework, and only fully completed responses were analyzed. The questionnaire was administered digitally via LimeSurvey to $N = 178$ learners, ranging from secondary school students ($N = 53$) to university students ($N = 125$) in Germany. Recruitment was based on voluntary participation following an open call to educational institutions, and thus, a nonprobability sampling approach was employed.

1. Secondary school students

Participants were predominantly students from secondary schools in Germany. Responses were received from various regions across Germany. Students attended different schools and were included independently of their prior performance or specialization, provided they had received regular curricular instruction covering wave optics, with polarization being a commonly included topic. No comparative assessment of their prior knowledge relative to the broader student population was conducted, as no restrictions or selection thresholds were applied. Gender was not collected. Ages reflected the typical ranges for the respective grade levels: mainly 17–19 years of age.

2. University students

The parallel university student sample was recruited from higher-education institutions across Germany. As with the school sample, participation was voluntary and not based on probabilistic selection procedures. Students came from various semesters and degree programs, specifically physics and physics-related studies. Gender was not collected.

TABLE III. Results of the confirmatory factor analysis on the model level for both models under investigation.

Criterion	Cutoff value	One-factor model	Two-factor model
χ^2	...	496.87	247.97
df	...	230	199
p	...	<0.001	0.12
CFI	≥ 0.95	0.68	0.96
SRMR	≤ 0.08	0.10	0.07
RMSEA	≤ 0.05	0.07	0.03
AIC	...	11214	10509
BIC	...	11360	10681

B. Data analysis regarding RQ1

In order to assess the fit between the data and the theoretical structure proposed by the Fidelities Model of Conceptual Development, we carried out a confirmatory factor analysis (CFA) in order to confirm construct validity based on the methodological approach taken by Bitzenbauer and Ubben [14]. The statistical calculation was performed in R 4.4.3, initially assuming a multivariate normal distribution. To test this, Mardia’s test from the included mvn 6.1 package was used. Since the test showed a violation of normal distribution, a robust maximum likelihood estimator was used for further analysis by implementing the Yuan-Bentler mean-adjusted estimator from the LAVAAN 0.6-19 package [cf. [34,35]].

1. Global model fit

The global model fit was assessed using a set of standard indices, including the χ^2 goodness-of-fit test, CFI (comparative fit index), RMSEA (root mean square error of approximation), and SRMR (standardized root mean residual). To interpret model fit, we applied the cutoff values recommended by Schermelleh-Engel *et al.* [36] and Cho *et al.* [37], which are provided alongside their values for the different models in Table III. To systematically evaluate both model fit and complexity, we employed a dual approach incorporating information-theoretic indices and statistical comparison. Specifically, we calculated the Akaike information criterion (AIC) and the Bayesian information criterion (BIC) to assess competing model specifications. These criteria penalize overparameterization, thereby discouraging unnecessarily complex models and promoting parsimony [38]. While AIC is oriented toward optimizing predictive accuracy, BIC applies a stronger penalty for model complexity, which is particularly relevant in large sample contexts, thereby favoring more concise models [39]. To supplement these metrics with a formal inferential test, we additionally performed likelihood ratio tests (LRTs), which are designed to evaluate whether a nested, more complex model yields a statistically superior fit compared to a simpler baseline.

By integrating AIC, BIC, and LRTs, our model comparison strategy balanced predictive performance, model simplicity, and statistical significance, resulting in a more robust basis for model selection [cf. [40]].

2. Local model fit

To evaluate local model fit at the level of individual indicators, we analyzed standardized factor loadings (λ), associated error variances (computed as $1 - \lambda^2$), and the squared loadings (λ^2) as measures of item reliability. Cross-loadings were not permitted during model specification. Items exhibiting standardized loadings below 0.30 were excluded from the final model, following the recommendation by Kline [41]. Reliability at the latent construct level was assessed using McDonald's omega (ω), which offers a more appropriate estimate than Cronbach's alpha when factor loadings are nonuniform across indicators [42]. A reliability threshold of $\omega > 0.70$ was applied to indicate acceptable internal consistency of the respective scale [cf. [42]]. Furthermore, we computed the average extracted variance (AEV) for each latent construct to evaluate convergent and discriminant validity. The AEV quantifies the proportion of variance in the observed indicators that is attributable to the underlying construct, relative to the proportion attributable to measurement error [cf. [43]]. As proposed by Fornell and Larcker [44], discriminant validity can be considered adequate when a construct's AEV exceeds its squared correlations with any other construct in the model.

To enhance the CFA with a broader perspective on the data, we also report key descriptive statistics, including response distributions, means, medians, and standard deviations for each indicator.

C. Data analysis regarding RQ2

To address research question 2, we first examined basic descriptive statistics for all indicators, including the distribution of responses, arithmetic means, standard deviations (SD), and median values. We then used the results of the CFA to analyze students' mental models by positioning them within the type grid described in Sec. III, assigning positions based on their composite FF and FG scores and thereby mapping the distribution across the four types. For this purpose, we derived two composite metrics representing the respective latent constructs based on the factor loadings (λ)—the FF score for factor FF and the FG score for factor FG. These scores were calculated as weighted averages of the observed indicators F_i and G_i , with weights corresponding to the standardized factor loadings λ_i :

$$\text{FF-Score} = \frac{\sum_{i=1}^{11} \lambda_i \cdot F_i}{\sum_{i=1}^{11} \lambda_i}$$

and

$$\text{FG-Score} = \frac{\sum_{i=1}^{11} \lambda_i \cdot G_i}{\sum_{i=1}^{11} \lambda_i}.$$

This weighting method ensures that indicators with higher loading, i.e., those more strongly associated with the latent factor, contribute more substantially to the corresponding composite score.

Finally, to examine potential differences in their scores, students were categorized into two groups—secondary school learners and higher education—and FG as well as FF scores between both groups were compared. Because the assumption of normality was not met, we refrained from t tests and instead conducted the nonparametric Mann–Whitney U test. Results are reported in the format $[U(N_1, N_2) = U, p; r]$, where U is the test statistic, N_1 and N_2 are the sample sizes of the respective groups, p is the corresponding p value, and r denotes the effect size [cf. [45]]. The strength of significant effects is expressed via the rank-biserial correlation coefficient r . Following Kerby's [46] guidelines, values of $0.2 < r < 0.4$ indicate medium effects, while $r \geq 0.4$ denotes large effects.

VI. RESULTS

A. Results regarding the global model fit

In Table III, an overview of the two tested models and their corresponding fit indices is given. Simplifying the model, i.e., going from the two-factor to the one-factor model, results in a noticeable decline in the CFI, signaling a degradation in model fit. This pattern is further underscored by rising values in both the SRMR and RMSEA, which consistently point to reduced fit quality. Notably, the two-factor model not only produces a lower chi-square statistic but also satisfies all conventional fit indices listed in the second column—in contrast to the one-factor model. In addition, the likelihood ratio test (performed with `lavTestLRT` of the `LAVAN` package) confirmed that the two-factor model provides a significantly better fit than the one-factor solution ($p < 0.001$). Comparing the Bayesian and Akaike information criteria, both values are lower in the two-factor model further attesting to better equilibrium of fit and parsimony. Taken together, the two-factor model exhibits significantly improved fit; hence, we will focus on this model and report local fit statistics in the following section.

B. Results regarding the local model fit

Table IV summarizes the local fit indices, including estimates at the item level and corresponding reliability coefficients. The model was identified by setting the variances of the latent variables to one, which allowed all item-factor relationships to be estimated without constraints [cf. [14]]. As the second column containing the factor loading of each item shows, all remaining items of

TABLE IV. Results of the confirmatory factor analysis for the two-factor model including item estimates (i.e., factor loadings, standard error, and error variance) as well as reliability calculations (i.e., indicator reliability, factor reliability, and average extracted variance).

	Indicator	Factor loading (Standard error)	Error variance	Indicator reliability	Factor reliability ω	AEV
FF	F01	0.425 (0.080)	0.820	0.180	0.71	0.20
	F02	0.517 (0.069)	0.733	0.267		
	F03	0.604 (0.074)	0.636	0.364		
	F04	0.496 (0.091)	0.754	0.346		
	F05	0.390 (0.079)	0.848	0.152		
	F06	0.502 (0.075)	0.748	0.252		
	F07	0.470 (0.077)	0.779	0.221		
	F08	0.473 (0.074)	0.776	0.224		
	F09	0.388 (0.075)	0.850	0.150		
	F10	0.341 (0.079)	0.884	0.116		
	F11	0.351 (0.097)	0.877	0.123		
FG	G01	0.498 (0.078)	0.752	0.248	0.81	0.29
	G02	0.558 (0.084)	0.689	0.311		
	G03	0.404 (0.081)	0.837	0.163		
	G04	0.564 (0.071)	0.681	0.319		
	G05	0.656 (0.078)	0.570	0.430		
	G06	0.391 (0.103)	0.847	0.153		
	G07	0.721 (0.063)	0.481	0.519		
	G08	0.599 (0.077)	0.642	0.358		
	G09	0.413 (0.093)	0.830	0.170		
	G10	0.408 (0.089)	0.833	0.167		
	G11	0.511 (0.076)	0.739	0.261		

the model satisfy the model constraints determined in Sec. V B 2. Those factor loadings range from 0.341 (F10) to 0.604 (F03) on the FF scale and 0.391 (G06) to 0.721 (G07) on the FG scale. McDonald's ω as an estimator of internal consistency was $\omega_{FG} = 0.81$ for the scale on Fidelity of Gestalt and $\omega_{FF} = 0.71$ for the scale on

Functional Fidelity. The intercorrelation between the two factors was 0.43, and its square was exceeded by the AEV of either factor ($0.18 < 0.20 = \text{AEV}_{FF} < 0.29 = \text{AEV}_{FG}$), thereby satisfying the Fornell–Larcker criterion for discriminant validity. The corresponding path diagram for this model is displayed in Fig. 3.

In summary, the findings of the confirmatory factor analysis support a two-dimensional structure underlying students' mental models of linear polarization. The final sets of items can be found in Tables VII and VIII.

C. Results regarding RQ2

In order to address the second research question, we investigated the sample in further detail. The descriptive statistics including mean values, standard deviations, and agreement/disagreement percentages are presented in Table V. The mean values on the FF scale range from 2.92 (F11) to 3.62 (F07) and the FG scale from 1.87 (G02) to 2.99 (G11), which shows an overall higher agreement on the Functional Fidelity scale. This is also reflected in the median and agreement percentages, more often manifesting toward high agreement with median values varying between 3 and 4 for the FF scale, as well as a more reserved answer median between 2 and 3 and nearly equal agreement and disagreement percentages, respectively. A type grid in terms of the fidelities model for the cohort,

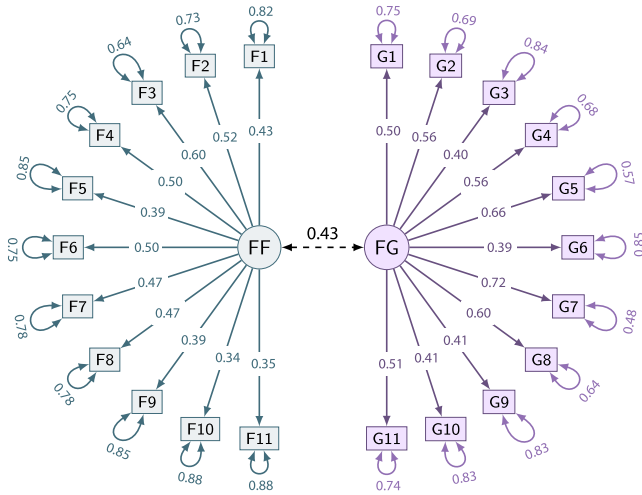


FIG. 3. Path diagram of the two-factor model. Numbers on the single-sided arrows indicate standardized factor loadings. The numbers on the double-sided arrows indicate error variances of the respective item. The correlation between both factors is 0.43.

TABLE V. Descriptive statistics including mean, standard deviation (SD), median (Mdn). Additionally, the table shows the percentage of student's agreements (+, rating: 3 = rather agree or 4 = agree) and disagreements (−, rating: 2 = rather disagree or 1 = disagree) for all items. Descriptive statistics for the metrics FF and FG score are provided in the last row, respectively.

Indicator	Mean±SD	Mean	SD	Mdn	+	−
F01	1 —●— 4	3.42	0.91	4	83.71	16.29
F02	1 —●— 4	3.50	0.78	4	87.64	12.36
F03	1 —●— 4	3.39	0.83	4	85.39	14.61
F04	1 —●— 4	3.12	1.02	3	73.60	26.40
F05	1 —●— 4	3.19	0.94	3	80.34	19.66
F06	1 —●— 4	3.17	1.01	3.5	78.09	21.91
F07	1 —●— 4	3.62	0.80	4	89.89	10.11
F08	1 —●— 4	3.03	0.92	3	75.28	24.72
F09	1 —●— 4	3.53	0.80	4	88.20	11.80
F10	1 —●— 4	3.38	0.84	4	86.52	13.48
F11	1 —●— 4	2.92	1.18	3	65.17	34.83
FF score	1 —●— 4	3.31	0.48	3.36	...	...
G01	1 —●— 4	2.51	1.03	3	52.25	47.75
G02	1 —●— 4	1.87	1.04	2	24.72	75.28
G03	1 —●— 4	3.03	1.08	3	71.91	28.09
G04	1 —●— 4	2.22	1.11	2	41.57	58.43
G05	1 —●— 4	2.53	1.20	3	52.25	47.75
G06	1 —●— 4	2.84	1.10	3	66.29	33.71
G07	1 —●— 4	2.40	1.20	2	48.31	51.69
G08	1 —●— 4	2.66	1.15	3	57.30	42.70
G09	1 —●— 4	2.48	1.16	3	53.93	46.07
G10	1 —●— 4	2.90	1.13	3	65.17	34.83
G11	1 —●— 4	2.99	0.98	3	73.60	26.40
FG score	1 —●— 4	2.55	0.67	2.64	...	...

presenting the individual weighted scores, is depicted in Fig. 4. Dominance of the dual (55.06%) and functional (39.89%) type is clearly observable within the sample. Especially the dual type, resulting in an orientation of the data within the first quadrant, is clearly shown. Only a small percentage (5.05%) of the cohort is situated in the undeveloped or architectural type.

The descriptive results of the Mann-Whitney U test shown in Table VI solidify the trend which Fig. 4 is showing: The purple nodes representing secondary students exhibit less of functionally developed thinking, while older students represented by the blue nodes show less Gestalt-wise thinking. The Mann-Whitney U test underpins this by means of an empirical argument, with higher values for university students than secondary students on the FF score [$U(53, 125) = 1587, p < 0.001; r = 0.52$] with high statistical significance, while the results are reversed for the FG score [$U(53, 125) = 2002, p < 0.001; r = 0.40$]. The box plots in Figs. 5 and 6 provide a more detailed overview of the distribution of responses. In these figures, we adhere to the established standard of limiting the length of the whiskers to 1.5 times the interquartile range.

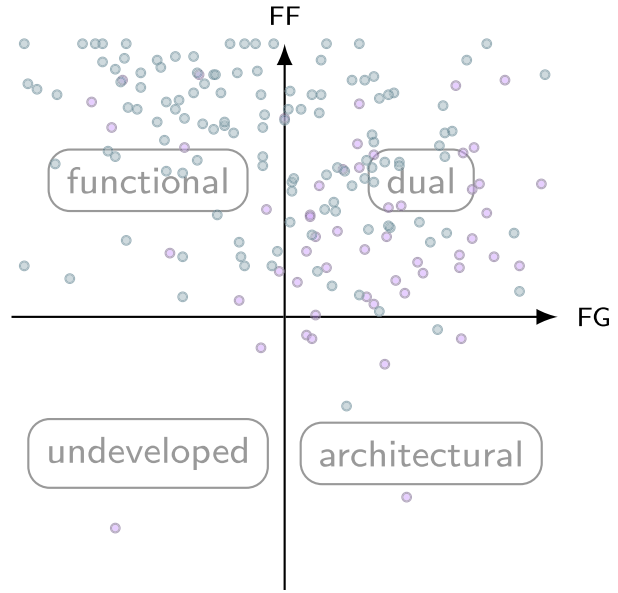


FIG. 4. Type grid of the fidelities model for the entire sample. Purple dots: secondary school students ranging in age between 17 and 19. Blue dots: higher physics education learners being of over 20 years of age.

VII. DISCUSSION

A. Discussion regarding RQ1

Evaluating the results of the confirmatory factor analysis, the data support the theorized two-factor structure among learners' mental models of linear polarization. All conventional cutoff criteria, as presented in Table III, are well satisfied by a CFI of 0.96, a SRMR of 0.07 and a RMSEA of 0.03, indicating a good fit of the model to the data. In comparison, the one-factor model reflects values usually interpreted as a poor fit ($CFI = 0.68 < 0.95$; $SRMR = 0.10 > 0.08$; $RMSEA = 0.07 > 0.05$), which further supports the two-factorial framework. Also, the p -values of both goodness-of-fit tests indicate different model fit: While for the one-factor model, a significant deviation from the given data is observed ($p < 0.001$), the p -value of 0.12 accompanying the two-factor model continues to substantiate the fit of said model to the dataset. When examining information-theoretic criteria like the Akaike information criterion (AIC) or the Bayesian information criterion (BIC), the two-factor model also is favored due to its lower values indicating a more balanced proportion of complexity and explanatory power. Both the scale on Functional Fidelity and Fidelity of Gestalt exhibit strong and acceptable factor reliabilities using McDonalds $\omega > 0.70$ [42]. As previously described, another indicator of convergent and discriminant validity is the average extracted variance (AEV), which is considered adequate when it exceeds the squared correlations with any other construct in the model, in order to quantify the amount of internal variance explained by the latent constructs. In this

TABLE VI. The results of the Mann-Whitney U test are presented alongside descriptive statistics including the cohort sample sizes, mean values, standard deviation (SD), and standard error (SE). Additionally, the U statistic, p values, and the corresponding effect sizes are provided.

	Cohort	N	Mean	SD	SE	Test statistic	p	r
FF	School students	53	3.00	0.48	0.07	1587	<0.001	0.52
	University students	125	3.43	0.51	0.05			
FG	School students	53	2.87	0.61	0.08	2002	<0.001	0.40
	University students	125	2.40	0.68	0.06			

instance, the average extracted variances of both factors therefore have to exceed the squared intercorrelation between the factors FF and FG: Comparing the square of the intercorrelation $0.43^2 = 0.18 < 0.20 = \text{AEV}_{\text{FF}} < 0.29 = \text{AEV}_{\text{FG}}$ with the AEV of both factors, this criterion is met supporting discriminant validity. Looking at the remaining items using the distribution across the identified subdomains (see Table II), the complete coverage in combination with the empirical results provides a valid test instrument. Comparing these findings to those of

Ubben and Bitzenbauer on quantum mental models where, for example, the intercorrelation between factors also showed a value of 0.42 as well as even exceeding factor reliabilities regarding each latent construct [cf. [14]]. Also, looking further back to Ubben and Heusler in 2019 [5], the analysis yields results similar to those reported for the subtopic of atomic physics. Because the presented data align well with research so far and closely connects to the immediate content neighbor of quantum physics, one may safely argue that the Fidelities Model of Conceptual Development can be applied to the topic of linear polarization in classical and quantum optics education.

B. Discussion regarding RQ2

The present results point to two key findings. First, with increasing age, there is a clear change in the way mental models are interpreted. Second, although school education appears to promote the abstraction of mental models, this effect is less pronounced than with university education. The resulting structuring of these models makes it possible to understand the underlying learning processes in a more differentiated way. The increase in abstract mental models, i.e., a decrease in Fidelity of Gestalt, observed with increasing age is consistent with the current understanding of the psychological development of working memory [47–50] as well as with the hypothesized conceptual development trajectory in the FMCD framework (cf. Fig. 1). This finding additionally supports the development of abstract thinking skills as schooling progresses. In this regard, an obvious reason for the shift toward functional aspects in the interpretation of mental models instead of pictorial ones is the time component. In-depth, long-term engagement with a topic provides the opportunity to change perspectives and using different representations, visualizations, and models. The dissolution of increasingly graphic representations can therefore develop naturally with increasing time and engagement. This relationship is substantiated by recent findings indicating that conceptual understanding is positively correlated with Functional Fidelity in mental models [5,14,29]. It is further noteworthy that findings also point to the fact that even formally highly educated learners (at the end of a master's degree or similar) are not necessarily much more elaborate in their interpretations of their mental models than secondary

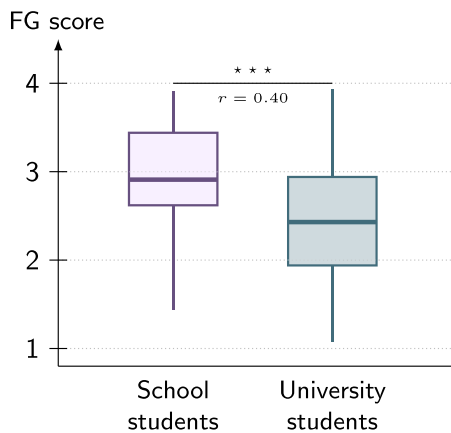


FIG. 5. Boxplots for the composite metric FG score split by cohort.

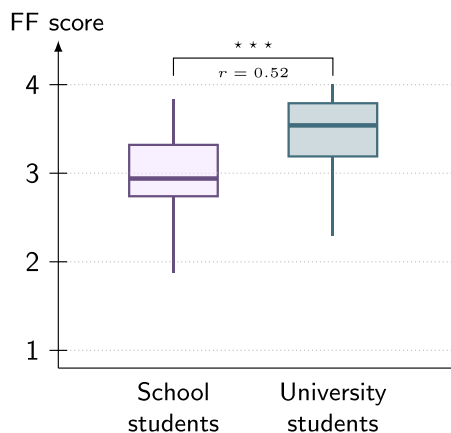


FIG. 6. Boxplots for the composite metric FF score split by cohort.

school students [51–53]. This ties in with the findings of the work of Veith *et al.*, where the most developed type in mental models also seems to be the dual type [29,54]. At first glance, this finding appears counterintuitive, particularly in light of the commonly assumed differences between school and university physics education. The following considerations therefore aim to provide a contextual framing of the observed results. They do not constitute causal explanations but are intended to outline plausible conditions under which such developmental plateaus in mental model interpretation may persist. One possible contextual factor could be that taking a metaperspective on physics plays a greater role in higher education, as the learning formats are strongly geared toward independent exchange rather than prestructured content [55]. Higher education is also generally much more technical and computationally intensive than physics lessons at school, which are largely qualitative, as the parallel science of mathematics cannot be assumed [55]. Thus, the functional aspects in higher education naturally emerge, while in school, the focus is on imagery when advanced tasks largely follow the operators “describe,” “justify,” or “sketch” [55–57]. Courses that explicitly address modeling and epistemological issues promote a significantly more reflective metaperspective on physics, which is one of the inherent differences between school and university [cf. [56]]. Even though multiple representations in terms of modeling processes were not incorporated in our study design, we feel that this notion provides substantial explanatory power for our findings. Thus, in the following, we want to hypothesize on the role of multiple representations. The moderating function of Gestalt and Fidelity of Gestalt in the interpretation and handling of mental models, as well as their significant influence on the abstraction process via multiple representations, has already been hypothesized in works like Zhang [58], Schwonke *et al.* [59], or Sima *et al.* [60]. Moreover, it can be gathered from those mentioned sources that appropriately selected visualization methods do not hinder learning but rather facilitate the process of abstraction. The results of our study can at least be seen as indications in the same direction. In order to make clear statements in this regard, however, a more in-depth cohort analysis must be carried out to clearly distinguish between the variables of age and education. To summarize in the words of Bitzenbauer and Ubben: “[T]he Gestalt-Function hypothesis points to the proposed theoretical description of conceptual development from Type I to Type IV through envisioning, functional discovery, and abstraction” [14] (p. 15), whereby images (or other modal patterns) develop from initial approximations via representations of a concept to carriers of functionalities [cf. [14]]. This has potential implications for educational practice. The insights gained here enable teachers to develop a more nuanced understanding of their students’ thinking and modeling patterns. In addition, there are indications that it could be useful to

introduce flexible and comparative work with models at an early stage, which supports the development of the corresponding viable mental models and their interpretation [17]. Abstraction does not arise automatically through school education, but through the reflective use of models over time, whereby form is both a resource and a limitation. Possible directions for future research, derived from these assumed dynamics, are elaborated upon in the outlook. Overall, the findings show that the dimensions of Functional Fidelity and Fidelity of Gestalt are suitable for structuring learners’ mental models in a differentiated manner. At the same time, the most important factors influencing these dimensions remain largely hypothetical. If the goal of physics education is to improve learning processes regardless of the length of training, it is worth taking a closer look at the structure and genesis of mental models. Contributing factors alongside the role of time, like how learning is structured, modeling processes or multiple representations may be promising in this regard.

VIII. LIMITATIONS

The present findings contribute valuable perspectives on students’ mental models of conceptions of linear polarization through the fidelities model. Nonetheless, several methodological and conceptual constraints should be considered. With respect to RQ1, the exclusive use of Likert-scale self-report items introduces limitations in capturing the full scope of students’ mental models. While confirmatory factor analysis supported the proposed model structure, this methodological approach may overlook subtleties in how learners apply these models in problem-solving scenarios. Incorporating qualitative techniques, such as think-aloud interviews or student reflections, alongside the statistical endeavors could enhance the interpretive depth of future investigations. Regarding RQ2, the study’s cross-sectional nature limits its explanatory power regarding individual developmental change. Although age-related variations could be identified, longitudinal data would be required to ascertain whether these reflect stable learning trajectories over time.

Further, although the presented model posits a clear distinction between reasoning grounded in Fidelity of Gestalt and Functional Fidelity, students’ thought processes may not always align with this binary categorization. It remains possible that mixed or integrated forms of reasoning exist but are not adequately represented within the current measurement setup. Another limitation of this study concerns the overall sampling strategy. Participation from both secondary school and university students across Germany was obtained through voluntary response to an open call to educational institutions. Consequently, the study relies on a nonprobability sample, which cannot easily be assumed to represent the broader student population. The findings should therefore not be overgeneralized beyond the groups that took part.

This sampling approach is appropriate for the exploratory character of the study, yet it inherently may introduce self-selection biases. This study adopts an observational approach without incorporating instructional interventions. Consequently, it does not offer insights into the potential impact of specific teaching strategies on learners' transitions between mental model types. To address this gap, future research could employ experimental or design-based methodologies to investigate how targeted pedagogical measures might support the development from Gestalt-driven reasoning toward more functionally abstract conceptions. Also, the results do not allow clear conclusions to be drawn about the causes of the observed interpretative shift. The data represent trends within a specific cohort that, although representative of its field, only provide indications and does not allow causal relationships to be established. This limitation makes it clear that additional research approaches are needed to more precisely identify the mechanisms behind the changes identified. In conclusion, although the findings lend support to the fidelities model within the transition from wave optics to quantum optics learning, further investigation is required to advance the framework conceptually, broaden its range of application, and more directly examine its relevance for instructional practice.

IX. CONCLUSION AND OUTLOOK

In conclusion, this research provides empirical grounds to justify and continue the use of the Fidelities Model of Conceptual Development within the physics subdomain of linear polarization in optics. Specifically, the confirmatory factor analysis supports the proposed two-factor framework, describing students' mental models in terms of varying manifestations of Fidelity of Gestalt and Functional Fidelity. The results thus lend empirical support to the theoretical distinction underlying the model and demonstrate that these dimensions can be meaningfully operationalized. With respect to RQ1, the findings provide clear evidence for the validity of the developed test instrument. The confirmed two-factor structure indicates that students' functional and structural conceptions of linear polarization can be reliably captured through the item set. In this regard, the instrument proves suitable for diagnosing mental models along the dimensions of Fidelity of Gestalt and Functional Fidelity within the investigated context. Beyond instrument validation, the study identified trends related to age and depth of education. Among secondary school students, high levels of both Functional Fidelity and Fidelity of Gestalt were observed, whereas older learners tended to exhibit increasingly function-oriented interpretations accompanied by a reduction in Fidelity of Gestalt. These results point to systematic differences in how mental models are interpreted across educational stages. However, no claims are made that these trends are influenced exclusively by the conditions discussed in this study, nor do the results permit causal

conclusions regarding the underlying mechanisms. While the findings contribute to a deeper understanding of students' mental models, the study does not provide concrete instructional strategies for promoting either dimension of understanding. Instead, it offers empirically validated scales that allow for the systematic assessment of Functional Fidelity and Fidelity of Gestalt in the context of linear light polarization. At the same time, the results raise several questions that point toward future research directions. Since the data cannot answer, but only hint at, whether the two strongly underrepresented mental model types—undeveloped and architectural—occur more frequently in younger learners, future studies should consider including younger age groups. For such investigations, however, the choice of topics within the field of optics may need to be reconsidered to ensure age-appropriate access to the underlying concepts. Moreover, the findings prompt further inquiry into how learners can be supported in developing functional ways of thinking. In this context, instructional approaches that foster intuitive understanding followed by systematic transitions toward abstraction—such as genetic teaching and learning sequences—appear particularly promising and are already gaining increasing attention in physics education research [8,61]. On a theoretical level, the study underscores the need to examine more closely the role of multiple representations in terms of modeling processes, as well as other factors correlated with age, in the development of mental models. Of particular relevance is how such factors contribute to the structuring of mental models and how they interact with dimensions such as Fidelity of Gestalt and Functional Fidelity. The observed connection between age, schooling, and mental model interpretation further suggests that time and accumulated experience may act as key drivers in this developmental process. This opens up opportunities to systematically investigate additional variables, such as the number and diversity of representations learners encounter.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

J. S.: conceptualization, methodology, formal analysis, investigation, data curation, writing—original draft; J. V.: conceptualization, writing—review and editing, visualization, supervision; P. B.: conceptualization, writing—review and editing, supervision.

APPENDIX: FINAL SCALES

TABLE VII. Developed items for testing Functional Fidelity on linear polarization. The items are to be answered on a four-point rating scale ranging from “I do not agree at all” = 1 to “I completely agree” = 4. For the purpose of this report, the items were translated from their original form in German. Therefore, it is possible that certain linguistic intricacies are lost in translation.

FF scale	Item
F01	Polarizers do not change the color of light, only its direction of oscillation and intensity.
F02	The light intensity after a polarizer depends on the angle between the light's polarization and the polarizer axis.
F03	With multiple polarizers, the angles between their axes determine the light intensity.
F04	Polarization describes the direction in which the electric field of the light oscillates.
F05	The polarization of light is influenced by the interaction of light with matter.
F06	A polarizer influences both the intensity of the light and the direction of oscillation of the electromagnetic wave.
F07	Through one or the combination of multiple polarizers, the polarization of light can be deliberately changed.
F08	The projection of the oscillation onto the polarizer axis determines what intensity is measurable behind the polarizer.
F09	Unpolarized light contains components of all oscillation directions.
F10	Polarization is evidence that light can be described as a wave whose oscillation direction can be changed by external influences.
F11	Only transverse waves like light exhibit polarization, as their oscillation direction is perpendicular to the direction of propagation.

TABLE VIII. Developed items for testing Fidelity of Gestalt on linear polarization. The items are to be answered on a graduated agreement-scale combined with numerical representations ranging from “I do not agree at all” = 1 to “I completely agree” = 4. For the purpose of this report the items were translated from their original form in German. Therefore, it is possible that certain linguistic intricacies are lost in translation.

FG scale	Item
G01	At a 45° polarizer, the light beam is filtered so that only the diagonally aligned oscillations between the grid bars can pass.
G02	Light that hits a polarizer at an angle to the polarizer axis is completely blocked.
G03	A polarizer acts like a grid that only lets light pass through in one particular direction.
G04	Light rays are like arrows that only pass through the grid of the polarizer when they point in the same direction.
G05	The polarizer only lets through light that is aligned exactly like the direction of the grid lines inside the polarizer.
G06	A polarizer lets light through that matches its polarizer axis and blocks all else, reducing intensity.
G07	Polarizers block all light whose polarization direction does not precisely match the polarizer axis.
G08	A polarizer is like a fence that only lets light rays through that are parallel to the bars.
G09	The more polarizers are placed in sequence, the darker the light gets, because more of it is cut away.
G10	If two polarizers are rotated relative to each other, the light becomes dimmer.
G11	A polarizer acts like a sieve that lets only specific light rays through.

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