Review Article

Phenomenographic approach to understanding students' learning in physics education

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[This paper is part of the Focused Collection on Qualitative Methods in PER: A Critical Examination.] Inquiring about students' learning and their difficulties understanding the concepts and models of physics is a familiar challenge in physics education research. Researchers have developed various methodologies, such as phenomenography, to address it. Phenomenography is an empirical approach to determining how people experience and understand aspects of their surroundings and the physical world in qualitatively different ways. Rigorous phenomenographic analysis can be used to define categories to describe general ways the students experience the research phenomenon. The phenomenographic analysis process focuses on critical aspects of the collective experience rather than the richness of individual experience, assuming that there are a limited number of categories to describe the variations of experience for a given phenomenon. The possibility of defining a limited number of categories for experiencing a phenomenon on a collective level is one characteristic that makes phenomenographic analysis particularly appropriate for research that aims to enhance teaching and learning. We shall critically examine the strengths and weaknesses of phenomenographic research in this paper. The strengths include integral and holistic descriptions of people's conceptions. Weaknesses include the risks of equating participants' experiences with their descriptions of their own experiences. Our contribution weighs up the literature's warnings about the validity and reliability of phenomenographic research. To provide an overview of phenomenography in physics education research, we conducted a literature review which identified and analyzed different approaches to data collection, data analysis, rigor, presentation of the results, and scope. We conclude by considering phenomenography as a research approach to learn how students perceive a concrete learning phenomenon, thus, providing an essential teaching design and preparation guide for instructors.

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I. INTRODUCTION

Phenomenography is an empirical approach to determining the qualitatively different ways individuals experience and understand aspects of the world around them [1,2]. Phenomenography is a relatively new approach to educational research. In its Swedish form, it was not until the mid-1970s that phenomenography grew out of concerns to improve curricula by probing student conceptions [3,4]. Marton and Säljö focused phenomenography toward educational research [3]. In the literature, this approach to improve the curriculum by investigating students' conceptions [5–8] is called Martonian phenomenography [1]. This article refers to Martonian phenomenography because our analysis focuses on research into the processes of teaching and learning physics.

However, Martonian phenomenography initially emerged as a research focus from a strongly empirical basis that was more theoretical or philosophical. In fact, only recently, developments have clearly looked at epistemological and ontological suppositions, a theoretical basis, and specification of methodological requirements [9–11]. Methodological debates have become more frequent over the last few decades, which has led to clarification of cases and methods accepted in the practice of phenomenography [12]. However, the lack of publications in the physics education research area that review the fundamental elements and the accepted variation in phenomenographic practice might lead to confusion on the nature of the focus.

To address these questions, this document first reviews the epistemological and ontological assumptions and the methodological characteristics of the phenomenography, focusing on the points of view expressed in the literature

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from the mid-1990s onwards. This review presents both the common points and the variations in the methods between phenomenographic researchers. Second, this review focuses on studies published in physics education publications. We will conclude by emphasizing the fundamental characteristics of the phenomenographic focus in PER literature, elucidating the implications of the common points and the variations in accepted phenomenographic practice in the literature.

In each section of this article, we delve into more detail on these and other characteristics of phenomenography. In Sec. II, we analyze the ontological and epistemological foundations of phenomenography. Next, we address the characteristics of the phenomenographic methodology, its strengths and weaknesses, and some issues related to the validity and reliability of phenomenographic studies. Section IV presents a review and discussion of research with a phenomenographic approach to physics teaching. Finally, there is a discussion about the possibilities and opportunities of adopting a phenomenographic approach to physics education research.

II. DESCRIPTION OF THE PHENOMENOGRAPHIC METHODOLOGY

A. Ontological and epistemological assumptions of phenomenography

The primary purpose of phenomenographic research is to perceive different ways of understanding a given phenomenon. From a phenomenographic perspective, a phenomenon represents "the combination of different ways in which an aspect of the world is conceived or experienced" by a group of individuals [13]. Phenomenography holds a nondualistic view of human awareness, conceptualized as a human-world relationship. This contrasts with other ontological approaches, such as objectivism and subjectivism. Objectivist ontology states that phenomena and their meaning are independent of social actors, thereby making a complete explanation of reality. Objectivism may underestimate the crucial role of agency (i.e., the human capacity to act on informed choices) by portraying a social entity as external to the individual, with its own reality. On the contrary, subjectivist ontology assumes that learning is a mental process; therefore, reality lies in the mind [14]. Consequently, subjectivist and objectivist perspectives have a dualistic view of nature because they focus on an internal or external world to explain the other. However, for phenomenography, the world cannot be the same in the absence of the person experiencing it, and conversely, the person cannot be the same if the world being experienced does not exist.

The ontological concern of phenomenography is the relationship between awareness and reality. This means that the only world that individuals can communicate about is the world that they experience. Therefore, if a phenomenon is outside of their experience or awareness, then they do not know that it exists. Reality in phenomenographic reasoning exists through how a person perceives it [15]. Therefore, conceptions of phenomenography refer to ideas built in the mind, and the individual's context and environment influence this construction. Phenomenography does not offer universal principles about the nature of knowledge or reality because one individual's reality differs from another's, not fixed in space and time. This implies that the conception of a specific phenomenon can change over time because the input and thought processes depend on experience. Emphasizing the dynamic nature and contextual sensitivity of individuals' conceptions of a specific phenomenon is thereby essential in phenomenographic research [16]. Learning is associated with a change in discernment, which entails a change in the aspect or aspects of the phenomenon in the student's awareness. This implies a change in how the phenomenon is experienced [17].

Because of the nondualistic ontological position of phenomenography, phenomenographic epistemology focuses on the content of descriptions revealed by individuals experiencing phenomena. This experiential epistemology emphasizes interaction between the knower and the known; it implies creation and negotiation rather than discovery and verification [18]. Phenomenographic epistemology takes into account the principle of intentionality. Intentionality means that knowledge cannot exist independently of a knower, and an individual's awareness is always directed towards something other than himself; that is, the individual has an objective [1]. For example, a language learner, whose main goal is to pass an exam, may implement specific learning strategies such as repetition, note taking, and memorization, although these strategies may not be useful for someone else's learning objective in a different learning environment.

Since phenomenography is concerned with the individual's knowledge of reality (an ontological issue) and their expression of reality (an epistemological issue), phenomenography encompasses a second-order perspective (i.e., how the individual conceives the world) instead of a first-order perspective. Marton [6] suggests that, in the second-order perspective, research is oriented toward (and makes claims about) people's ideas about the world. This contrasts with the first-order perspective, where research is oriented toward the world and makes claims about it. From a second-order perspective, the world is described as it is understood rather than as it is. A phenomenon is also viewed through the subject's awareness and reflections rather than the researcher's or society's views. In this sense, the data and findings of phenomenographic study are essentially based on the participants' reports coming from their awareness and conceptions of the world. This epistemological characteristic may be why phenomenography has mainly been applied in studies related to education.

B. Methodological characteristics in phenomenography

According to the ontological and epistemological characteristics described, the phenomenographic methodology collects data on how a person experiences a phenomenon as described by that person. A data collection method must be particularly appropriate in a strategy that makes it easier for a person to reflect on their experience of a phenomenon. First, a standard phenomenographic study informs the participants about the phenomenon. Using this knowledge, the person is invited to reflect on their experience of the phenomenon or activity. The person is asked to reflect on their experience (consciously) to characterize the phenomenon and distinguish it from the whole [15]. As phenomenography aims to categorize the different ways students experience a phenomenon or topic, the data collection instruments should address a common theme shared between the researcher and the students [16].

Phenomenography employs specific methods for data collection, analysis, and results representation. Many options are available, and we have included three which are often used to collect information: interviews, open questionnaires, and products or works created by students [19,20]. Here is a brief overview of the types of instruments and a discussion of some affordances and risks for each.

(1) Interviews: the standard phenomenographic interview is semistructured, with minimal set questions, and it focuses on how the interviewees experience the topic rather than on the person or the topic. The researcher should create an environment where participants feel comfortable discussing all aspects of a phenomenon. A phenomenographic interview differs from other types of interviews in two key ways: (a) the relationship between the person being interviewed and the topic of the interview (i.e., the person being interviewed experiences the phenomenon, which is the topic of the interview), and (b) a focus on how people experience the issue rather than the person or the issue itself [15].

(2) Open-ended questionnaires: researchers should propose open-ended questions to allow participants to present their understanding and experience with the phenomenon. The questions address the essence of experiences, such as learning experiences. When data are collected through an open questionnaire, phenomenographic research interprets the concepts. The basic principle of analysis is to understand the meanings in their context and on their terms, however difficult it may seem [9].

(3) Reports of students' activities: when the instruments are reports of students' activities, such as homework or transcribed video recordings of in-class discussions. The data collection focuses on capturing the different explanations given by the students or the processes that they perform. In this type of data collection, students are familiar with the work or product and the phenomenon they are explaining [19,20].

Each instrument has affordances and risks that must be considered before choosing a data collection procedure. The chosen instrument must be coherent with the research objectives. Interviews give phenomenographic researchers the chance to ask participants to elaborate on something they said. However, researchers' preconceived ideas can present a bias risk during interviews. For example, a nonphenomenographic researcher might ignore opinions expressed by participants which do not fit the researcher's preconceived ideas. A phenomenographic researcher must avoid preconceived ideas by empathizing and considering those points of view as highly interesting instead [21,22]. This risk might be avoided in open-ended questionnaires, although they provide no opportunity to delve further into specific experiences. In this type of instrument, researchers must take a second-order perspective and describe the phenomenon as experienced by the individual. There is a risk of imposing preconceived ideas during data analysis, rather than during data collection. When analyzing documents, affordances and risks can be very diverse. For example, when analyzing a video recording of an in-class discussion, one affordance might be that the explanations take place in a natural context, while the risks might be related to participants' awareness of the recording. The affordances and risks of analyzing students' homework would be very different. From this analysis, the key takeaways are that (i) researchers need to be aware of the affordances and risks of their instruments before choosing one, and (ii) imposing preconceived ideas at any stage (and very importantly, during data collection and when precategorizing the data) should be avoided to prevent the data description categories from being shaped by researcher bias and to reveal the respondents' understanding of the phenomenon.

Another critical issue in phenomenographic research is the type of sample chosen. To answer this question, one must consider that a phenomenographic study explicitly intends for the participants to have experienced the given phenomenon. Here, variations are also accepted on the choice of sample within the phenomenographic approach. Convenience sampling can provide the best data for the full scope of the various ways of experiencing the phenomenon [23]. In convenience sampling, the most suitable individuals are chosen to act as respondents until the required sample size can be obtained [14]. The researchers establish specific criteria to select the respondents and thus obtain data to analyze the various ways of experiencing the phenomenon. Concerning sample size, Cohen, Manion, and Morrison [14] explain: "the researcher simply chooses the sample from those to whom she has easy access. As it does not represent any group apart from itself, it does not seek to generalize about the wider population; for a convenience sample that is an irrelevance. The researcher, of course, must take pains to report this point that the parameters of generalizability in this type of sample are negligible. A convenience sample may be the sampling strategy selected for a case study or a series of case studies" (p. 119).

Phenomenographic analysis generally begins with a search for meaning and its variations in interview transcripts or written responses to questions and reports. It is then complemented by a search for structural relationships between the variations of meaning. Some phenomenographic researchers emphasize the importance of not prioritizing the search for structure too early in the process. Conversely, others highlight the danger of not considering structure until too late in the process, since meaning and structure are interrelated in phenomenographic analysis [8,23,24]. One main feature of how the different explanatory categories are constituted is the search for key qualitative characteristics within the category and differences between categories. This is a complex process where students' transcripts and writings are grouped and regrouped according to perceived similarities and differences throughout the analysis. Thus, a variety of nuances enter the validation and verification procedures to establish explanatory categories that are contrasted with the data, adjusted, contrasted again, and readjusted to establish a global system of meanings [8]. In the next section, we shall describe the results of the phenomenographic research in more detail.

It is important to highlight variations in practice between investigators when performing phenomenographic analysis [23]. Variations can relate to different aspects of the analysis. We shall describe three aspects widely mentioned in the literature [25].

- There are variations in the length of the transcripts or scripts when interpreting data segments. On the one hand, some researchers favor breaking the transcripts into smaller chunks because they consider that a full-transcription approach might reduce the clarity of key aspects. On the other hand, other researchers prefer complete transcripts or scripts because the interpretations must be treated as a set of interrelated meanings.
- Another aspect that offers diversity of choice is the emphasis on conducting the analysis individually or by a group of researchers. While many phenomenographic researchers work individually during data analysis, the subjectivity of this form of interpretation has inevitably been roundly criticized by quantitative researchers. It is relevant to acknowledge here that the crucial element in phenomenographic analysis lies in identifying and describing the different conceptions and that any outcome space is inevitably partial, regarding the hypothetically complete range of ways of experiencing a phenomenon. When we talk about better or worse results, we are referring to outcome spaces at different levels of completion. Therefore, an individual researcher can, as a minimum, contribute substantially to our understanding of a phenomenon [26]. As indicated by various authors, this does not exclude that a group research project might produce a better outcome [23].
- Another aspect that causes variation in data analysis is different researchers' approach when reading students' descriptions or reviewing description categories. These wide-ranging approaches include the following: (i) focusing on the meanings of the description categories; (ii) focusing on the "how" and "what" of the phenomenon description, and (iii) focusing on the similarities and differences of each description category.

These approaches are not exclusive, nor do they describe all the approaches in the literature, but they do give an idea of the diversity in phenomenographic analysis. However, when we talk about the variations and nuances in the analysis here, we are talking about the researchers' efforts to complete the outcome space.

Despite this diversity, the literature explicitly indicates that there is a common practice in phenomenographic research that clearly defines what is from what is not phenomenographic research [3,5,6,8,15,23,25]. Phenomenographic practice considers common elements of analysis, such as keeping an open mind during the analysis, minimizing any predetermined point of view, and beginning the analysis with a search for meaning or variation of meanings based on the available data. The entire process is highly iterative and comparative, which involves continuous classification and reorganization of data, categories, and relations between categories. The literature recommends making the steps taken in phenomenographic research as explicit as possible to be able to comprehensively communicate the results, and their validity and reliability. Green and Bowden recommend research guidelines [27], which have been summarized and completed with other contributions in seven steps by Orgill [24]. These guidelines should be understood as the most comprehensive way of reporting the analysis process explicitly, not as a judgment regarding whether the results are correct or incorrect.

C. Results of the phenomenographic research: Description category and outcome space

Phenomenography studies the variation in the meaning people give to experiencing a particular phenomenon. The research results are analytically represented as a set of qualitatively different ways of experiencing the phenomenon. This set is called "description categories" which represent the different ways of empirically interpreting the phenomenon that is experienced [5,6]. Phenomenography proposes that the ways of experiencing represent a relationship between experiencing and the phenomenon that is experienced. This relationship means that the different description categories are logically related through the common phenomenon that is experienced. Therefore, one central premise of phenomenography is that description categories are logically related to each other through inclusive structural relationships [15]. Consequently, phenomenography outcomes include structural relationships that link the different description categories. These relationships form the structure of the so-called "outcome space" which aims to elucidate the relationships and variations between the different ways of experiencing the phenomenon. The outcome space shows the relationship between the different description categories, according to the logical complexity and its inclusive character, and describes the various possible ways of experiencing the phenomenon. Interest in logical relationships between description categories is a characteristic of learning progress in school. Standard phenomenographic studies display an outcome space by mapping conceptions of a population, not an individual.

According to Marton and Booth [15], there are two central distinctions between description categories and individual conceptions in phenomenographic research. The phenomenographer creates description categories to represent the participants' collective conceptions as faithfully as possible. Second, each description category focuses on the critical aspects of understanding a given phenomenon that differentiate it from other ways of experiencing it. Individuals' conceptions may encompass aspects related to multiple categories or refer to another phenomenon.

Phenomenographic research, encompassing many empirical studies in the literature, affirms that the ways people experience or see a phenomenon, although qualitatively different, are limited in number [6,11]. This is because a "phenomenon" contains a limited number of discernible aspects. If this were not so, people would not be able to identify the specific phenomenon, and therefore, we would not be able to communicate effectively; each person would live in a different world. Furthermore, individuals are limited in their abilities to simultaneously distinguish and be aware of all possible ways of understanding a phenomenon [15]. Thus, although an individual's awareness of a phenomenon is theoretically infinite and therefore open to new modes of experience, natural limitations are based on prior awareness of that phenomenon. Likewise, individuals within a population share similar contextual environments; therefore, a certain degree of understanding and limitation in understanding might be assumed.

In summary, there are two clear parts to phenomenographic data analysis. The first forms the description categories and the second develops the outcome space that graphically illustrates the categories' relationship and possible hierarchy [19]. The main result of phenomenographic research is an outcome space that comprises a set of related description categories for a specific phenomenon. Each description category describes a different way of experiencing or viewing a phenomenon, which can be generalized across different situations for the same phenomenon [6]. In Sec. III. B, we present some examples that illustrate the process of creating description categories and outcome spaces that might be useful for researchers.

1. Description category

As indicated by Marton and Booth [15], description categories should not be confused with students' "conceptions". The phenomenographic perspective considers "conception" as the awareness of the phenomenon to be learned, established as an experiential relationship between the student and the phenomenon. The relationships between the different conceptual categories are structurally related in a hierarchy of inclusiveness [7]. A description category is a construct created by the researcher to represent the participants' conceptions as faithfully as possible at a collective level. This supra-individual system of ways of thinking describes human thought in two ways. First, it can be used to describe how people think in concrete situations. Second, it can be seen as a description of thought [28]. Data analysis leads to qualitatively separate categories defining how research subjects experience the phenomenon. These categories arise from analyzing the data obtained by the different instruments (interviews, open-ended questionnaires, and/or documents).

2. Outcome space

The outcome space is where the description categories represent how they are logically related. Equally important, the outcome space also indicates the internal consistency of the categories themselves [23]. During the analysis, constant examination of the internal and external logic guides the iterative construction of the description categories and, therefore, the outcome space [15]. The similarities and differences when experiencing and understanding a phenomenon can be seen as "a collective intellect that forms a structured set of ideas, beliefs, and facts that underlie a reflection and interpretation of reality" [11]. The outcome space usually gives rise to a reduced number of categories described in a way that shows how they relate to each other.

In the phenomenographic outcome space, structural relationships are hierarchically inclusive. Some categories are more advanced and complex than others [8]. Marton and Booth [15] present three primary criteria for judging the quality of a phenomenographic outcome space:

- Each category in the outcome space reveals something distinctive about understanding the topic.
- The categories are logically related, typically as a structurally inclusive hierarchy of relationships.
- The results are parsimonious; a minimal set of categories represents the critical variation of the experience observed in the data.

The process is markedly iterative and comparative. The iterative nature involves looking at the data from different perspectives at different times. The comparative involves continual classification and reclassification of data, comparisons between data and descriptive categories, and comparison between the categories themselves [4].

D. Phenomenographic research rigor: strengths and weaknesses

The literature has highlighted the advantages of phenomenographic research as a tool for understanding the various ways in which students conceptualize a scientific concept. Phenomenographic research allows students' conceptions to be mapped into descriptive categories and used in teaching-learning sequences. Phenomenography has become a popular qualitative research method in higher education, as students' experiences of a phenomenon are described in terms of a relationship between that person and the specific concept. The relational quality of the conception reflects the context in which the phenomenon is inserted. One of the main advantages of phenomenography is its realism because it seeks to generate a range of possible ways to experience a particular phenomenon rather than seeking a single understanding of it [29]. An explanatory category has the advantage of being two-dimensional: one dimension focuses on the content of the topic (the referential aspect), and the other focuses on how a student understands the content (the structural aspect) [18].

Various authors indicate that the main problem with phenomenography revolves around equating the participants' experiences with their accounts of said experiences. The critique focuses on working out how far the outcome space structure emerges from the data or reflects the researchers' judgment. For Åkerlind [4], this criticism is only a matter of degree since the outcome space is constructed with the data obtained and the researcher's interpretive judgment. The phenomenographic approach does not focus on the phenomenon as it really exists but on human experience of the phenomenon. For this reason, phenomenography never sees an interpretive process as objective as it represents the data as experienced by the researcher.

Phenomenography is qualitative research; therefore, it shares the same underlying assumptions. Qualitative research arguments are used when addressing validity and reliability issues [14]. Criticism concerning the validity and reliability of phenomenographic research is discussed below [30–32].

1. Validity of the design

Validity refers to how much the research results reflect the study phenomenon. The first question revolves around the size of the phenomenographic sample, in other words, the number of people in the sample who are asked about their experience of a particular phenomenon to ensure a reasonable chance of finding a wide-ranging variation in categories. Åkerlind [33] indicates that the experience of multiple phenomenographic studies shows empirical evidence that between ten and twenty people are usually sufficient to capture the category variation range as long as the sample is appropriately selected to maximize variation. Another argument often mentioned is "theoretical saturation," i.e., when data collected on the situations being observed appear to be repeating data already collected [[14], p. 331]. Of course, it may be important to carry on collecting data at this point, to indicate overall frequencies of observed behavior, enabling the researcher to find the most to the least common behaviors observed over time [34]. The greater the number of observations, the greater the data reliability might be, enabling verification of emergent categories. Some studies that use open-ended questionnaires show that, as more people are surveyed, there is a tendency for the categories to stabilize, and new categories are unlikely to emerge (see Table II and below comments).

Concerning validity, phenomenography falls within qualitative research in general and, as such, must incorporate specific strategies for verifying the validity of the phenomenographic design [30]. One type of validity check used in phenomenography is called communicative validity. This type of validity justifies and defends the research methods and the findings of the studies by holding an open dialogue with the participants, other members of the professional community, and the audience of the research results [14,35]. In particular, the interview question design is warranted by different means, such as peer validation, pilot interviews, and questionnaire trials. It also reports how an unbiased sample was chosen. When using convenience samples, the participants' characteristics should be clearly stated, providing background for any attempt to extend the results to other contexts.

Another type of check used in the phenomenographic methodology is pragmatic validity, which tries to explore how useful and significant the results of a phenomenographic study are for the intended audience. Insights gained from research results are pragmatically valid if they provide valuable knowledge that can be used by the intended audience [36].

2. Analysis reliability

From a qualitative research perspective, reliability can be seen as the use of appropriate methodological procedures to ensure quality and consistency in data interpretations. Regarding data analysis reliability, phenomenographic studies follow two main forms of verification [24]. Both include the use of multiple investigators to assess or balance the potential impact of an individual investigator interpreting the data. The first form of reliability focuses on several researchers comparing the data sample coding (coder reliability check) [11]. In the second, researchers manage to agree on the interpretative categories through discussion and critique of the data and the interpretative hypotheses (dialogic reliability) [8]. Both forms of reliability are used with varying degrees of popularity, and by including various elements. A common alternative to these forms of reliability verification is for the researchers to clarify their interpretative steps in detail.

Orgill [24] compiles the different proposals in seven steps that help to explicitly present data analysis, validity, and reliability that can help researchers to report phenomenographic research explicitly. The first is known as familiarization. The researcher reads and rereads the interview transcripts or the written responses to open-ended questionnaires to become familiar with the content. The second step involves answering specific questions. This stage identifies the most significant characteristics of the given answers. The third stage is condensation or reduction to find the central parts of the interview or written responses. The fourth step is the initial classification of similar answers, and the fifth step comprises the preliminary comparison of categories. The sixth step names the categories. The seventh contrasts and compares the categories and includes a description of the nature of each category nature and any similarities or differences among them.

Common meanings are presented as categories, compared, and grouped as an expression of understanding. No single description category can be attributed to individuals; their collective understanding is described in the study's results. Additional measures are taken after preliminary development of the description categories. Through rigorous reexamination of the collected data, the researcher can modify, add, or remove categories or refine their descriptions. This process continues to the point where the categories appear to be consistent with the data collected from the interviews, open-ended questionnaires or documents. The results are presented to facilitate informed scrutiny, and the description categories are fully articulated and adequately cited [37].

When two or more researchers discuss both the data and the research results, dialogic reliability is used, which refers to reaching a common understanding of the former and an agreement on the latter [14,35]. Zuza *et al.* [38] explain the application of dialogic reliability to investigate university students' understanding of electromagnetic induction. They assigned two investigators who independently defined preliminary description categories. Cohen's kappa reliability coefficient was calculated to measure agreement on the criteria by the two researchers to establish the preliminary categories. If the match was inadequate, the two researchers discussed their assignments and went back to making preliminary categories. The rest of the research team reread the questionnaire responses and independently made tentative classifications of each transcript into categories. The classifications were compared, and where disagreements arose on the description categories or classification into categories, these were resolved, taking the transcripts as the only evidence of student understanding. The development of this iterative group approach to the analysis of phenomenographic data allows for new insights into the description categories for the phenomenon being analyzed. The same type of analysis was performed for the interview transcripts.

Some studies combine the phenomenographic method with a specific theory in the analytical process. In the case of Campos *et al.* [39], the phenomenographic method was combined with a theoretical structure relevant to the theoretical framework that guided the research. However, it is essential to note that the description categories emerged from the data and were classified into the theoretical structure *a posteriori*. The theoretical structure revealed relations between categories that emerged in questions with different characteristics and corresponded to the seventh step in the analytical process.

III. PHENOMENOGRAPHY IN THE PER LITERATURE

A. Review protocol

We conducted a literature review to illustrate how the phenomenographic method has been used in the physics education research literature. This review can guide early-career researchers who intend to perform phenomenographic research on their methodological choices in their topic of interest. The review was conducted in the Scopus database with the query: (ALL(phenomenograph*) AND SRCTITLE(physics)). This query includes articles with words related to phenomenography (i.e., phenomenography or phenomenographic) anywhere in the text in journals that include the word physics (e.g., American Journal of Physics or Physical Review Physics Education Research). This query provides a representative overview of the use of phenomenography in physics education research literature. However, it is not comprehensive because we did not include science or science, technology, engineering, and mathematics (STEM) education journals, which partially contribute to the field of PER. The use of phenomenography in science or STEM education journals is beyond the scope of this contribution. Moreover, it is possible that studies using the phenomenographic method in the last decades have not reported it as such. To reduce the risk of bias, such articles are also out of the scope of this literature review.

We retrieved 138 articles and decided to include articles with phenomenography anywhere in the text because, in many cases, the phenomenographic method is not stated in the title, abstract, or keywords but in the methodology section within the full text. We wanted to consider articles that might not include the term in these key metadata (title, abstract, or keywords). However, this decision had the disadvantage of selecting all articles that mentioned phenomenography in the literature review or the references even though this was not the primary research methodology. One of the researchers screened the articles and discarded them if phenomenography was not the main research method, primarily by identifying where in the article the word "phenomenography" appeared. The article was discarded if the word only appeared in the literature review and references but was not stated in the methodology. After this screening, the database was reduced to 40 articles. We subsequently checked for coherence that all the articles referred to Martonian phenomenography.

TABLE I. Review protocol.

Protocol for analysis	Description
Country	The country where the study took place (not necessarily the same as the country of affiliation). If there is more than one, separate by commas. If the article does not specify, assume the same as affiliation.
Type of study	Empirical: A study performed with participants. Literature review: A study performed by analyzing the existing literature. Theoretical: Theoretical details of the topic or method.
Educational context	High school. University: Introductory. University: Intermediate or advanced. Graduate studies. Preservice physics teachers. In-service physics teachers.
Objective	Copy and paste the objective of the study. If the objective is not related to the phenomenographic analysis, indicate it explicitly and do not proceed. Mark in red for review.
Participants (N)	The number of participants involved.
Instruments	Clear definition of the instruments. For example, open-ended questionnaires, open-ended surveys, Likert-scale surveys, interviews, focus groups, observation protocols, etc. If there is more than one, separate by commas.
Data analysis	Definition of the data analysis strategy from the text in terms of 7 key steps of phenomenographic research.
Rigor	Information about the instrument validation and reliability of the analysis.
Intersection with other theories	Specify other theories involved in the analysis (not physics theories or models, but theories of understanding and pedagogy). If there is no other theory involved, leave it blank.
Main results	Do not list the main results. Identify the characteristics of the results, such as the description category, frequency, etc.
Physics topic	Identify the physics topic studied in the article.
Who analyzed	Write your name (who performed the analysis).

All research team members took part in the literature review as follows: one of the researchers reviewed 8 articles and created a review protocol based on information that could be extracted from the articles. The researchers all gathered to analyze and discuss the review protocol and suggested improvements and insight into the expected type of information. The protocol was refined, as presented in Table I. Each researcher analyzed 8 articles, following the review protocol independently. All the researchers gathered to discuss the findings of their review protocol usage and resolve any questions that emerged during the review process. All agreed to conduct a second round of reviews to ensure the validity of the literature review. For this second round, we made sure that two different reviewers reviewed each article and that each researcher reviewed articles previously reviewed by different researchers, equally distributed to reduce possible bias. As part of the second review, we added a validation protocol that included the previous review protocol and a column for expressing comments about the previous review's validation (such as agreement, disagreement, and suggestions for improvement).

The review and validation protocols and the equitable distribution among researchers in the two rounds of reviews reduced possible bias in the information extraction of this literature review. After the second revision round, the authors decided to discard 8 articles because the phenomenographic method was not the primary research method or did not provide the necessary information to be extracted. The final database (see Appendix) consisted of 32 articles, thoroughly analyzed and validated (Table IV in the Appendix).

B. Analysis of the reviewed literature

1. Descriptive analysis

The final database includes articles from 5 sources (Table V in the Appendix): American Journal of Physics (6.25%), European Journal of Physics (18.75%), Physical Review Physics Education Research (56.25%) (before 2016, Physical Review Special Topics—Physics Education Research), Physics Education (6.25%) and Physics Education Research Conference Proceedings

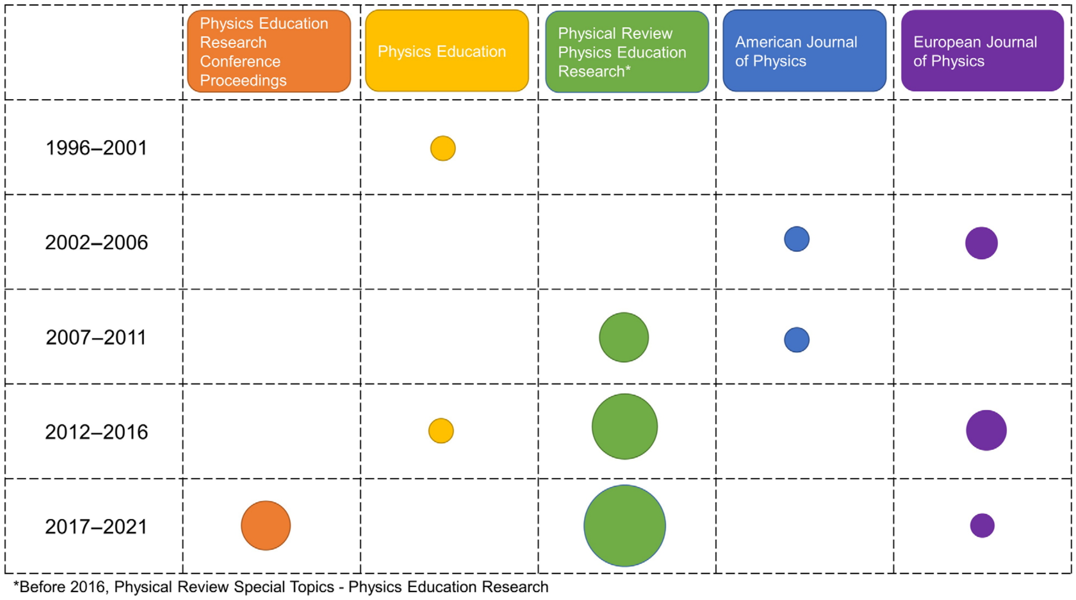

FIG. 1. Distribution of articles by source title and 5-year period.

(12.50%). These 5 sources are among the most relevant in the physics education research community. Figure 1 presents the distribution of articles by source and year. The analysis shows an increasing trend towards using phenomenography as a research method in physics education research.

Most articles that employ phenomenography have empirical objectives and methods (Table V). Only 1 out of 32 articles had a theoretical objective and used phenomenography as an analytical approach in a case study to support their theory [20]. This finding is evidence of the empirical nature of phenomenography because its primary objective is to identify the variation in the lived experiences or understanding of a phenomenon. The selected articles were mainly in the undergraduate context (78%), of which 14 studies were in introductory physics, and 10 were in intermediate or advanced physics courses. The remaining articles described other educational contexts, such as high school (2), preservice physics teachers (2), physics faculty (1), and others (2).

The geographical extent of the phenomenographic method in physics education research was predominantly in North America (50%) and Europe (40%), as shown in Fig. 2 and Table V. In North America, 14 studies were performed in the United States and 2 in Mexico. In Europe, Italy contributed 4 articles, Spain, Belgium, and Ireland published 1 article each and 2 jointly, Sweden contributed 2

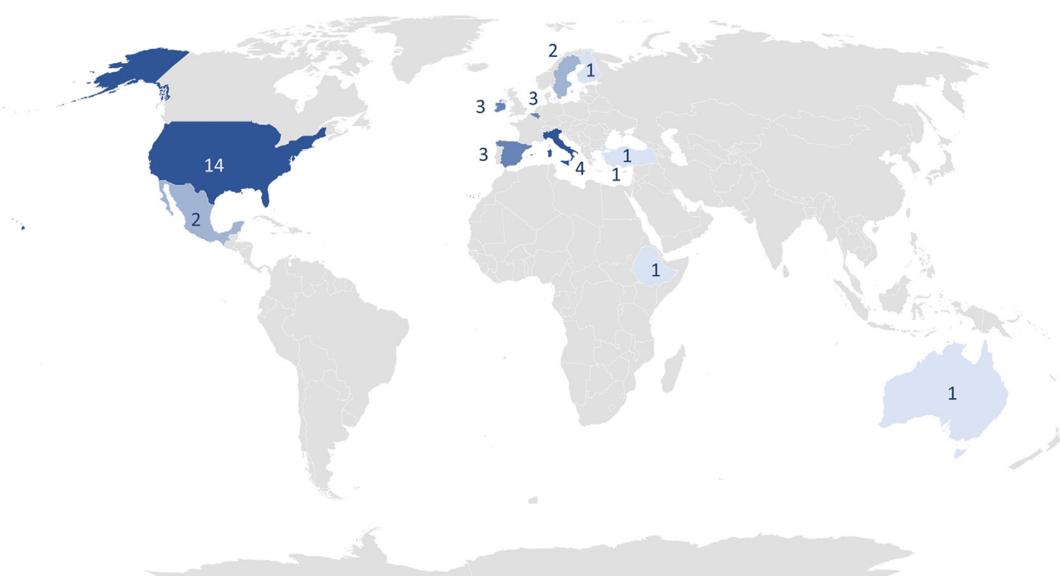

FIG. 2. The geographic extent of phenomenography in physics education research.

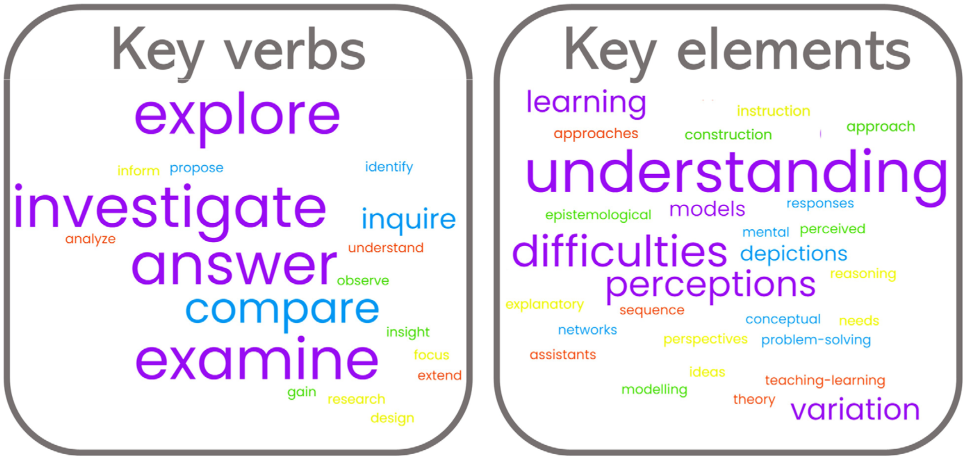

FIG. 3. Analysis of the study's objective by key verb and key elements.

studies, and Cyprus and Finland 1 study each. The European Union, as a whole, contributed 13 phenomenographic articles. In Southeast Europe and Western Asia, Turkey published 1 phenomenographic study. In Africa, we found 1 article from Ethiopia, and in Oceania, 1 article from Australia.

2. *Analysis of the methodological aspects*

In this subsection, we present an analysis of the objectives, the data collection (participants and instruments), the data analysis process, the rigor of phenomenographic research, and its intersection with theoretical frameworks. We analyzed the objectives of each study based on its key verb and the study element (see Fig. 3). To obtain the key verbs and elements, we sought the explicit objective declared by the authors in the introduction or the problem statement. For the key verb, we considered the main verb of the objective; whenever the study was only declared with research questions, we presented the verb as "answer." To obtain the key elements, we referred to the study object as declared in the objective. The detailed key verb and key element for each article are presented in Table VI in the Appendix. As shown in Fig. 3, the phenomenographic research objectives often include verbs such as to explore, investigate, examine or answer (specific research questions). The key elements often include students' understanding, difficulties and perceptions. Therefore, a guide for identifying a phenomenographic objective could be a combination of a key verb and a key element.

When analyzing the data collection process (Table VI), we found seven different instruments: open-ended questionnaires (44%), semistructured interviews (28%), open-ended surveys (13%), problem-solving questionnaires (6%), video recordings, homework questions, and group interviews (3% each). Six studies reported a combination of instruments. However, this analysis only focused on the main instrument reported. Table II analyzes the relation between the number of participants and the main instrument used in each study. We took $N = 30$ as the limit of participants proposed by [14] for quantitative research. Therefore, we present the number of articles that use each instrument for a range of 1 to 30 participants, 31 to 100 participants, and over 100 participants.

The evidence shows that phenomenography can be employed with qualitative instruments giving an in-depth interpretation of the phenomena (mainly semistructured interviews, group interviews, problem-solving questionnaires, and video recordings) with a small number of participants. This makes sense because of the time required for transcribing, cleaning, organizing, and analyzing such large amounts of data. Including more than 30 participants requires qualitative instruments that provide depth but also expand the scope of the instrument (such as open-ended questionnaires, open-ended surveys, and homework questions). It should be noted that using open-ended questionnaires meant the scope could exceed 100 participants. Attaining such quantities of qualitative data can help to generalize the results when sufficient rigor is guaranteed in the data analysis process. The data suggest that combining open-ended questionnaires (or surveys) with more than 100 participants and semistructured interviews with a smaller

TABLE II. Contrastive comparison of the number of participants and instruments used for conducting phenomenography in physics education research.

Instrument or number of participants	1–30	31–100	100+
Open-ended questionnaire	4	2	8
Semistructured interview	9		
Open-ended survey		2	2
Problem-solving questionnaires	1	1	
Video recordings	1		
Group interview	1		
Homework questions		1	
Total	16	6	10

subset (between 10 and 30 participants) would be ideal to generalize and understand the results in depth. We found this combination in 3 studies [40–42]. This addresses the reliability of the research [43]. Regarding the study review, the results match the literature to support interest in triangulation. Triangulation can be defined as using two or more data collection methods to study an aspect of human behavior [44]. If, for example, the results of a questionnaire survey correspond to the outcome of an observational study on the same phenomena, the researcher will trust the conclusions more. The advantage of the multimethod approach is that, given that the research methods act as filters through which the environment experiments selectively, they are never atheoretical or neutral when representing the work of the experiment; using different methods improves the results [45].

To analyze each study's approach to data analysis, for the reasons explained in Secs. II. B and II. D, we referred to the 7 steps for qualitative research proposed by Orgill [24]: Step 1: Familiarization, Step 2: Compilation, Step 3: Condensation, Step 4: Classification, Step 5: Comparison, Step 6: Naming, and Step 7: Contrastive comparison of categories. We identified whether each study reported on each of the steps (Table VII in the Appendix). In some studies, the data analysis process was not defined, and we classified it as "No steps." It is essential to clarify that if a study does not report a specific step (or any), this does not mean that they have not been performed nor that the research is incorrect. Instead, it measures the community's awareness of the importance of reporting every step of the analysis when performing phenomenographic research. The data analysis shows that after 2015, most studies reported at least 5 of the 7 steps, which was not the case before 2014. From 1996 to 2014, only 5 of 14 studies reported at least 5 steps, and only one reported all 7 steps. From 2015 to 2022, 11 out of 18 studies reported at least 5 steps, and 6 of 18 reported all 7 steps. This tendency demonstrates that awareness on reporting the data analysis process in phenomenographic research has increased recently. Table III shows the number of articles that presented each step before 2014 and after 2015. There is a clear increase in the number of articles reporting each step after 2015 and an apparent drop in articles that do not report the data analysis process. Furthermore, it is evident that the community finds it relevant to report steps 2 to 6, which makes sense because they are fundamental to reaching and populating the categories. Step 1, familiarization, is essential in every phenomenographic research project; however, it may seem too obvious when reporting the data analysis process. The seventh step, contrasting and comparing, is not always reported since some studies only describe the categories without comparing them.

We shall present two examples that report the phenomenographic steps with different results. Article A19 [38] describes the steps in the phenomenographic analysis in detail. It explains that one of the authors read the students' responses and identified categories for a small subset of responses (Steps 1 and 2: familiarization and compilation). After two weeks, the same researcher reread the students' responses and rechecked how they were assigned to the defined categories (Step 3: condensation). Next, all the authors met, discussed, and revised the categories, tested them on a second subset, and met, discussed, and revised them (Steps 4 and 5: classification and comparison). This process came to an end once a reasonably stable set of categories was obtained. Any disagreement about the description of the categories or the categorization of the responses was resolved by referring to the responses as the sole evidence of student understanding. An iterative process was used to produce the final descriptions of the categories that reflected the differences between them and ensured that the responses in each category represented similar understanding or reasoning. Likewise, the categories were named according to their main characteristics and are presented in the tables in order of their explanatory capacity per the scientific interpretation of the concept (Steps 6 and 7: naming and contrastive comparison).

Article A27 [46] exemplifies reporting the data analysis process and presenting results in an outcome space. This article reported the data analysis in five subsections. In the first subsection, "data reduction," the authors reported the first three steps: familiarization, compilation, and condensation. In the second subsection, "identification of preliminary themes," the authors provided a detailed account of the fourth step, classification. In the third subsection, "analysis of preliminary themes," they mentioned the fifth step, comparison, where they analyzed the emerging categories based on the variation between them and reported them neatly in tables. In the fourth subsection, "development of description categories," the authors reported the naming and contrastive comparison processes. These two processes are better understood in terms of the table where they report the final description categories. The first six steps identify and define the description categories. They are sufficient

TABLE III. Analysis of the steps of phenomenographic research reported in the literature.

Date range	N	No steps	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
1996–2014	14	6	4	6	5	7	6	6	3
2015–2022	18	1	10	16	15	12	11	16	9
Total	32	7	14	22	20	19	17	22	12

for reporting the categories, examples, and frequency. However, the seventh step is essential for presenting the results in an outcome space, a feature that this article reports explicitly [46].

To further ensure the quality of phenomenographic research, it is crucial to report the rigor followed in the data analysis process. Among the 32 articles in this review, 44% reported using interrater reliability (Cohen's kappa) as the measure to ensure the classification process (see Table VII), and 6% reported using interrater agreement (the statistic was not defined). In terms of creating categories, 22% reported validation among peers and 3% using the literature. The remaining 25% of articles did not report their evidence of quality assurance. In the previously analyzed examples, Zuza *et al.* [38] provided details of the rigor of the analysis by indicating that after defining the final categories, a very significant degree of agreement was reached on all questions: between 85% and 95% agreement between pairs of researchers, with a reliability coefficient mean (Cohen's kappa) of 0.83. In [46] the authors reported a fifth subsection of the data analysis process dedicated to validation through expert validation.

Variations in the analysis process can lead to differences in the rigor of the investigation (in these two examples, interrater reliability vs expert peer validation) and presentation of the results (a hierarchical structure vs an outcome space). It is essential to understand the analysis process to link it with the rigor of the phenomenographic research and the presentation of the results. By considering examples such as the two expressed above, we invite phenomenographic researchers to report every step of the data analysis process consistently in their studies because it is an essential aspect of phenomenographic research. Moreover, they should consider including the validation process as part of the analysis to ensure the rigor of their investigation.

One interesting aspect of phenomenography is its versatility in combining the methodology with other educational theories. In this database, 10 articles reported an intersection with another educational theory (Table VIII in the Appendix). The theoretical frameworks or standpoints that emerged in this analysis were: mental models, resources framework, the epistemic game framework, the conceptual blending framework, open-inquiry instruction, ontologies for identity, communities of practice, conceptual change, misconceptions framework, social semiotics, and the variation theory of learning. Some articles combined two or even three different theoretical standpoints. The resources framework was the most used theoretical framework as it emerged in 3 articles. However, it should be mentioned that, in general, the aim of qualitative research is not to test theories but to be able to generate new ones. One example in physics education research would be phenomenographic studies on how students interpret physical phenomena from the school curriculum. These studies have generated new knowledge on the nature of conceptions in learning and teaching [7,33]. More recently, phenomenographic studies have led to a theory of variation in learning and the conscience, with associated implications for learning and teaching approaches [16,47].

3. Analysis of the methodological scope

Phenomenography covers a broad scope of topics of interest in physics education research. We found that 25% of the studies focused on electromagnetism topics, 22% on classical mechanics, 16% on quantum physics, 6% on modern physics and thermodynamics, and 3% on statistical physics. We also found that 22% of the studies focused on an epistemological or psychological aspect of learning physics, such as perceptions of learning physics or being a physicist. The scope of each article is presented in Table VIII.

The presentation of the results is a definitive aspect of phenomenographic research, and it should focus on the descriptive categories and creating an outcome space when possible [6]. We analyzed how the various studies presented their results by identifying how many reported the descriptive categories, examples, frequencies, and outcome space (see Table VIII). We looked into any studies that might have reported their results differently and assigned them in the "Other" column (Table VIII). We found that 69% of the studies reported the descriptive categories, 84% provided examples for each category, 75% reported the frequency with which each category occurred, and 16% reported an outcome space. It should be noted that to identify the outcome space, we only included studies that reported category interrelations. Several studies reported a hierarchical definition of the descriptive categories, but we did not consider the hierarchical structure as an outcome space. For example, in [38] the authors presented a hierarchical structure of the categories. While they reported all the steps for phenomenographic research and the hierarchical structure represents the contrastive comparison of the categories, we did not consider it an outcome space because it does not express how all the categories are interrelated. One example of an outcome space would be as reported in [46], where the authors explicitly represent the sequential structure of the categories in a diagram. The authors of both articles were explicit about all the phenomenographic data analysis steps and reported the rigor presented in their research. A hierarchical structure efficiently represents the categories and how they relate to each other, while an outcome space creates a visual and explicit representation of the relationship between categories.

The articles that did not report descriptive categories (31%) coincided with the 10 articles that combined phenomenography with a theoretical framework. These articles were put in the "other" column because the authors reported a different coding structure related to the theoretical framework that they used. The coding structures that emerged in these articles were: mental models, resources, blends and representations, and multimodal semiotic systems, among others. This is a relevant finding because it implies that the intersection of phenomenography with other theories may lead researchers to define their categories differently. In phenomenographic research, the categories must emerge from the data and not from predefined conventions. This intends to dispense with categories that are largely preformed in researchers' thinking, although this does not rule out the legitimacy of using categorization diagrams derived from prior empirical studies or from theoretical models [48].

The intersection with theoretical frameworks provides the opportunity to shed light on the results, but it must be performed cautiously. Campos *et al.* [39] combined phenomenographic methods with the registers of semiotic representations theoretical framework. In this study, the objective was to compare students' conversion difficulties with three different representations. The problems presented to students were independent to avoid interference between representations. However, the comparison between conversion processes was not direct because of independent problems. In that case, the categories emerged from the data for each problem, and we later created a framework for structuring the descriptive categories based on the theory of registers of semiotic representations. This theoretical structure made it possible to compare students' conversion difficulties for the three representations and all the conversion directions when using independent problems. This example required a theoretical framework to achieve the study goal. We suggest that authors who perform phenomenographic research with one or several theoretical frameworks should let the descriptive categories emerge from the data and use the theoretical framework to create an outcome space.

IV. CONCLUDING REMARKS

In this article, we first described phenomenography's origin and epistemological and ontological foundations. Phenomenography refers to ideas built in the mind, and this construction is influenced by the context, the world (environment) in which each individual lives. The article describes how phenomenography is a qualitative research approach that provides the researcher with a rich, holistic, and varied understanding of how people conceive a phenomenon. This requires two distinct parts of data analysis. First, explanatory categories must be formed which describe how groups of students have experienced the given phenomenon. Second, the formation of the outcome space shows the relationship between the different categories of description, according to the logical complexity and its inclusive nature, and describes the variation of the possible ways of experiencing the phenomenon.

After determining the different steps of phenomenographic analysis and the strengths and weaknesses of the methodology, we conducted a review of research in physics education journals. We found an increase in studies in physics education using phenomenography as a research methodology; occasionally, it is combined with other educational theories. Although the best-known data collection instrument in phenomenography is the interview, in the reviewed sample, half of the investigations used open-ended or problem-solving questionnaires, which shows the variety of instruments that can be used. Likewise, in most of the studies over the last decade, each step of the phenomenographic analysis was consistently specified, which made data interpretation more transparent. These studies also showed concern for analytical rigor, reporting the validation arguments of the instruments and the reliability of the analysis.

The massification of higher education, permanent training, and the internationalization of curricula in the 21st century mean that the current student population is more heterogeneous than previous generations, particularly regarding preparation and expectations. In this situation, in-depth knowledge on how students learn about the curriculum topics is essential plus the types of ideas they receive from teaching. In this context, phenomenography could be essential for qualitative and semiqualitative research. Phenomenography allows us to delve into the various ways that a group (students) perceives certain phenomena taught in the curriculum. This knowledge helps teachers to build pedagogical approaches for a diverse and multicultural audience.

We want to indicate that phenomenography has developed a body of empirical research on students' conceptions that has helped to plan teaching strategies with different theoretical approaches over the years. Thus, information about the description categories has been used to design didactic tools such as learning demands based on a social-constructivist approach [49] and the design of teaching-learning sequences with different educational approaches such as the variation theory of learning [16], the framework theory [50] or, recently reformulated theories of conceptual change [51]. These pedagogical approaches and their effectiveness are beyond the scope of this article, so we only comment on the possible interest in pedagogical approaches that use the knowledge of students' explanatory categories obtained through phenomenography.

Furthermore, there is the possibility for phenomenographic research results to inform learning theory development in physics education research. While some results derived from phenomenographic research might inform theory development, this is not the main objective for conducting phenomenographic research which would be to understand qualitatively different ways in which people can experience a phenomenon. Other qualitative methods, such as grounded theory, aim to generate theoretical perspectives out of participants' responses [52].

One vital aspect to highlight is that studying phenomenography can allow researchers to discover the different ways in which people experience, interpret, or conceptualize various aspects of reality [6]. The affordances for physics education research that can derive from phenomenographic research are to have a clear understanding of the students' difficulties at hand, so that they can provide information to help improve learning materials. Phenomenographic research is not found at the macro level of research in education; in the review, we did not find research on the curriculum in educational institutions. This is because Martonian phenomenography always contemplates a context for learning that is assumed to be fairly uniform throughout the population studied, which limits studies at the "meso" level, in other words to certain groups that are quite homogeneous in terms of contents of curriculum and/or classes, but not in terms of background or intentions. So far, most research has been done at the "micro" level with relatively small groups of students, defining what individuals might interpret in given circumstances. If we consider that learning consists of transformations in experience brought about by the interaction of students' and teachers' points of view, understanding students' perspectives becomes an integral part of teaching practice. The wealth of explanatory categories can inform teachers about the critical aspects of the phenomena being taught and provide clues about the most appropriate pedagogical approaches for students to improve learning.

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APPENDIX

We include in the Appendix Tables IV–VIII, which summarize the final database for the literature review and its analysis.

TABLE IV. List of articles.

ID	Ref.	Authors	Title	Year	Source title
A1	[53]	Prosser M., Walker P., Millar R.	Differences in students' perceptions of learning physics	1996	Phys. Educ.
A2	[54]	Mannila K., Koponen I. T., Niskanen J. A.	Building a picture of students' conceptions of wave- and particle-like properties of quantum entities	2002	Eur. J. Phys.
A3	[55]	Rebello N. S., Zollman D.A.	The effect of distracters on student performance on the force concept inventory	2004	Am. J. Phys.
A4	[56]	Domert D., Linder C., Ingerman Å.	Probability as a conceptual hurdle to understanding one-dimensional quantum scattering and tunnelling	2005	Eur. J. Phys.
A5	[57]	Walsh L. N., Howard R. G., Bowe B.	Phenomenographic study of students' problem-solving approaches in physics	2007	PRST-PER
A6	[58]	Zacharia Z. C., Constantinou C. P.	Comparing the influence of physical and virtual manipulatives in the context of the Physics by Inquiry curriculum: The case of undergraduate students' conceptual understanding of heat and temperature	2008	Am. J. Phys.
A7	[59]	Hrepic Z., Zollman D. A., Rebello N. S.	Identifying students' mental models of sound propagation: The role of conceptual blending in understanding conceptual change	2010	PRST-PER

(Table continued)

TABLE IV. *(Continued)*

ID	Ref.	Authors	Title	Year	Source title
A8	[60]	Corpuz E. D., Rebello N. S.	Investigating students' mental models and knowledge construction of microscopic friction. I. Implications for curriculum design and development	2011	PRST-PER
A9	[61]	Ayene M., Kriek J., Damtie B.	Wave-particle duality and uncertainty principle: Phenomenographic categories of description of tertiary physics students' depictions	2011	PRST-PER
A10	[62]	Battaglia O.R., Fazio C., Sperandeo-Mineo R. M.	An inquiry-based approach to Maxwell distribution: A case study with engineering students	2013	Eur. J. Phys.
A11	[63]	Hu D., Rebello N. S.	Using conceptual blending to describe how students use mathematical integrals in physics	2013	PRST-PER
A12	[64]	Pizzolato N., Fazio C., Sperandeo Mineo R. M., Persano Adorno D.	Open-inquiry driven overcoming of epistemological difficulties in engineering undergraduates: A case study in the context of thermal science	2014	PRST-PER
A13	[65]	Malgieri M., Onorato P., Mascheretti P., De Ambrosis A.	Preservice teachers' approaches to a historical problem in mechanics	2014	Phys. Educ.
A14	[40]	Jones D. L., Zollman D.	Understanding vision: Students' use of light and optics resources	2014	Eur. J. Phys.
A15	[66]	Irving P. W., Sayre E. C.	Becoming a physicist: The roles of research, mindsets, and milestones in upper-division student perceptions	2015	PRST-PER
A16	[67]	Bollen L., Van Kampen P., De Cock M.	Students' difficulties with vector calculus in electrodynamics	2015	PRST-PER
A17	[68]	Madsen A., McKagan S. B., Martinuk M. S., Bell A., Sayre E. C.	Research-based assessment affordances and constraints: Perceptions of physics faculty	2016	PRPER
A18	[69]	Yerdelen-Damar S., Elby A.	Sophisticated epistemologies of physics vs high-stakes tests: How do elite high school students respond to competing influences about how to learn physics?	2016	PRPER
A19	[38]	Zuza K., De Cock M., Van Kampen P., Bollen L., Guisasola J.	University students' understanding of the electromotive force concept in the context of electromagnetic induction	2016	Eur. J. Phys.
A20	[41]	Malgieri M., Onorato P., De Ambrosis A.	Test on the effectiveness of the sum over paths approach in favoring the construction of an integrated knowledge of quantum physics in high school	2017	PRPER
A21	[70]	Zuza K., Van Kampen P., De Cock M., Kelly T., Guisasola J.	Introductory university physics students' understanding of some key characteristics of classical theory of the electromagnetic field	2018	PRPER
A22	[71]	Leak A. E., Williamson K., Moore D. L., Zwickl B.	On being a physics major: Student perceptions of physics difficulties, rewards, and motivations	2019	PERC Proceedings

(Table continued)

TABLE IV. *(Continued)*

ID	Ref.	Authors	Title	Year	Source title
A23	[72]	Hahn K. T., Emigh P. J., Gire E.	Sensemaking in special relativity: Developing new intuitions	2019	PERC Proceedings
A24	[73]	Goodhew L. M., Robertson A. D., Heron P. R. L., Scherr R. E.	Student conceptual resources for understanding mechanical wave propagation	2019	PRPER
A25	[19]	Alesandrini A. T., Heron P. R. L.	Types of explanations students use to explain answers to conceptual physics questions	2019	PERC Proceedings
A26	[74]	Zuza K., De Cock M., Van Kampen P., Kelly T., Guisasola J.	Guiding students towards an understanding of the electromotive force concept in electromagnetic phenomena through a teaching-learning sequence	2020	PRPER
A27	[46]	Pawlak A., Irving P. W., Caballero M. D.	Learning assistant approaches to teaching computational physics problems in a problem-based learning course	2020	PRPER
A28	[75]	Ruggieri C.	Students' use and perception of textbooks and online resources in introductory physics	2020	PRPER
A29	[20]	Eriksson M., Eriksson U., Linder C.	Using social semiotics and variation theory to analyse learning challenges in physics: A methodological case study	2020	Eur. J. Phys.
A30	[76]	Hernandez E., Campos E., Barniol P., Zavala G.	Comparing students' understanding of Gauss's and Ampere's laws with field sources in square-like symmetries	2021	PERC Proceedings
A31	[42]	Schermerhorn B. P., Sadaghiani H., Mansour A. E., Pollock S., Passante G.	Impact of problem context on students' concept definition of an expectation value	2021	PRPER
A32	[77]	Campos E., Hernandez E., Barniol P., Zavala G.	Phenomenographic analysis and comparison of students' conceptual understanding of electric and magnetic fields and the principle of superposition	2021	PRPER

TABLE V. Descriptive analysis: Country, type of study, and educational context.

ID	Country	Type of study	Educational context
A1	Australia	Empirical	University: Introductory
A2	Finland	Empirical	University: Intermediate or advanced
A3	United States	Empirical	University: Introductory
A4	Sweden	Empirical	University: Intermediate or advanced
A5	Ireland	Empirical	University: Introductory
A6	Cyprus	Empirical	Preservice physics teachers
A7	United States	Empirical	University: Introductory
A8	United States	Empirical	University: Intermediate or advanced
A9	Ethiopia	Empirical	University: Intermediate or advanced
A10	Italy	Empirical	University: Intermediate or advanced
A11	United States	Empirical	University: Introductory
A12	Italy	Empirical	University: Intermediate or advanced
A13	Italy	Empirical	Preservice physics teachers
A14	United States	Empirical	University: Introductory
A15	United States	Empirical	University: Intermediate or advanced
A16	Belgium	Empirical	University: Intermediate or advanced
A17	United States	Empirical	Physics Faculty
A18	Turkey	Empirical	High School
A19	Belgium, Spain, and Ireland	Empirical	University: Introductory
A20	Italy	Empirical	High School
A21	Belgium, Spain, and Ireland	Empirical	University: Introductory
A22	United States	Empirical	Other
A23	United States	Empirical	University: Intermediate or advanced
A24	United States	Empirical	University: Introductory
A25	United States	Empirical	University: Introductory
A26	Spain	Empirical	University: Introductory
A27	United States	Empirical	Other
A28	United States	Empirical	University: Introductory
A29	Sweden	Theoretical	University: Introductory
A30	Mexico	Empirical	University: Introductory
A31	United States	Empirical	University: Intermediate or advanced
A32	Mexico	Empirical	University: Introductory

TABLE VI. Analysis of data collection procedures: Objectives, participants, and instruments.

ID	Objective verb	Objective [element]	Range	Instrument
A1	Inquire	Students' perceptions	100+	Open-ended survey
A2	Identify	Students' conceptual network	1–30	Open-ended questionnaire
A3	Compare	Students' responses	100+	Open-ended questionnaire
A4	Investigate	Students' difficulties	1–30	Semistructured interview
A5	Answer	Students' problem-solving	1–30	Semistructured interview
A6	Compare	Students' understanding	31–100	Open-ended questionnaire
A7	Answer	Students' mental models	1–30	Semistructured interview
A8	Answer	Students' models	1–30	Semistructured interview
A9	Explore	Variation in students' depictions	1–30	Semistructured interview
A10	Propose	Learning approach	31–100	Open-ended questionnaire
A11	Investigate	Students' understanding	1–30	Group interview
A12	Investigate	Epistemological difficulties	1–30	Problem-solving questionnaire
A13	Observe	Students' understanding and modeling	1–30	Open-ended questionnaire
A14	Examine	Students' construction of understanding	31–100	Open-ended survey
A15	Examine	Students' perceptions	1–30	Semistructured interview
A16	Gain insight	Students' difficulties	1–30	Open-ended questionnaire
A17	Inquire	Faculty perceived needs	1–30	Semistructured interview

(Table continued)

TABLE VI. *(Continued)*

ID	Objective verb	Objective [element]	Range	Instrument
A18	Explore	Students’ perceptions	31–100	Open-ended survey
A19	Research	Students’ difficulties	100+	Open-ended questionnaire
A20	Focus	Students’ difficulties	1–30	Open-ended questionnaire
A21	Explore	Students’ explanatory ideas	100+	Open-ended questionnaire
A22	Examine	Students’ perspectives	100+	Open-ended questionnaire
A23	Answer	Student reasoning	31–100	Problem-solving questionnaire
A24	Inform	Instruction	100+	Open-ended questionnaire
A25	Examine	Variation in students’ depictions	31–100	Homework questions
A26	Design	Teaching-Learning Sequence	100+	Open-ended questionnaire
A27	Understand	Learning assistants’ approaches	1–30	Semistructured interview
A28	Investigate	Students’ perceptions	1–30	Semistructured interview
A29	Extend	Variation theory of learning	1–30	Video recordings
A30	Analyze	Students’ understanding	100+	Open-ended questionnaire
A31	Explore	Students’ understanding	100+	Open-ended survey
A32	Compare	Students’ understanding	100+	Open-ended questionnaire

TABLE VII. Analysis of data analysis strategy: reported steps, rigor, and intersection with other educational theories.

ID	No	S1	S2	S3	S4	S5	S6	S7	Rigor	Theory
A1			×	×	×	×		×	Interrater reliability	No
A2	×								No evidence	No
A3		×	×	×	×	×			Interrater reliability	No
A4			×				×		No evidence	No
A5		×	×	×	×	×	×		Validation among peers	No
A6							×		Interrater reliability	No
A7	×								Validation with literature	No
A8					×	×	×		Interrater reliability	Mental models
A9	×	×	×	×	×	×	×	×	No evidence	No
A10					×	×			Validation among peers	No
A11		×	×	×	×		×	×	No evidence	Resource, epistemic game, and conceptual blending
A12	×								Interrater reliability	Open-Inquiry instruction
A13	×								No evidence	No
A14	×								Interrater reliability	Resources framework
A15		×	×	×	×	×	×	×	Validation among peers	Ontologies for identity; communities of practice
A16			×	×	×	×	×		Interrater reliability	No
A17		×	×	×	×	×	×		Interrater agreement	No
A18			×	×	×		×		Interrater agreement	Epistemological resources framework
A19		×	×	×	×	×	×	×	Interrater reliability	No
A20	×								Interrater reliability	Conceptual change
A21		×	×	×	×	×	×	×	Interrater reliability	No
A22		×	×						Validation among peers	No
A23		×	×	×			×	×	No evidence	No
A24		×	×	×	×	×	×		Interrater reliability	Resources framework
A25			×	×			×		No evidence	No
A26		×	×	×	×	×	×	×	Interrater reliability	No
A27		×	×	×	×	×	×	×	Validation among peers	No
A28			×	×			×	×	No evidence	No
A29		×	×	×	×	×	×	×	Validation among peers	Social semiotics and variation theory of learning
A30			×	×	×	×	×		Interrater reliability	No
A31							×		Validation among peers	No
A32			×	×	×	×	×	×	Interrater reliability	Misconceptions framework

TABLE VIII. Analysis of data collection procedures: Physics topic and structure of the results regarding descriptive categories, examples, frequency, and the inclusion of an outcome space.

ID	Physics topic	Descriptive categories	Examples	Frequency	Outcome space	Other
A1	Epistemology // Psychology	Yes	Yes	Yes		
A2	Quantum physics	Yes		Yes	Conceptual maps	
A3	Classical mechanics	Yes		Yes		
A4	Quantum physics	Yes	Yes			
A5	Classical mechanics	Yes	Yes	Yes		
A6	Thermodynamics	Yes		Yes		Statistical analysis
A7	Classical mechanics		Yes	Yes	Interaction between categories	Mental models
A8	Modern Physics		Yes			Mental models
A9	Quantum physics	Yes	Yes	Yes		
A10	Statistical Physics	Yes		Yes		
A11	Electromagnetism		Yes			Blends and representations
A12	Thermodynamics			Yes		Typology
A13	Classical mechanics	Yes	Yes	Yes		
A14	Electromagnetism		Yes	Yes		Resources
A15	Epistemology // Psychology	Yes	Yes	Yes		Change over time
A16	Electromagnetism	Yes	Yes	Yes		
A17	Epistemology // Psychology	Yes	Yes	Yes		
A18	Epistemology // Psychology	Yes	Yes	Yes		Distribution of time allocation
A19	Electromagnetism	Yes	Yes	Yes		
A20	Quantum physics		Yes	Yes		Models
A21	Electromagnetism	Yes	Yes	Yes		
A22	Epistemology // Psychology		Yes	Yes		Codes
A23	Modern Physics		Yes			Rules of thumb
A24	Classical mechanics		Yes	Yes		Resources
A25	Classical mechanics	Yes	Yes			
A26	Electromagnetism	Yes	Yes	Yes		
A27	Epistemology // Psychology	Yes	Yes		Structure	
A28	Epistemology // Psychology	Yes	Yes		Patterns	
A29	Classical mechanics		Yes		Relevance structure	Multimodal semiotic systems
A30	Electromagnetism	Yes	Yes	Yes		
A31	Quantum physics	Yes	Yes	Yes		
A32	Electromagnetism	Yes	Yes	Yes		

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