Visual representation of optical content in China's and Singapore's junior secondary physics textbooks

Bing Wei,[*] Chengran Wang, and Lihua Tan

Faculty of Education, University of Macau, Taipa, 999078 Macau, China

(Received 6 August 2022; accepted 7 November 2022; published 28 November 2022)

Visual representation in school textbooks plays an important role for physics teaching and learning. The integration of graphics with text has drawn attention of physics educators in recent years due to the close relationship between graphics and relevant text. The purpose of this study is to examine visual representation of optical content in three physics textbooks commonly used in China and Singapore. Based on a revised version of graphical analysis protocol, this study focuses on two aspects of visual representation: (i) presentation of graphics, and (ii) integration of graphics with corresponding text. The content analysis approach was adopted as the research methodology with 115 graphics taken from the three physics textbooks being the analysis target. The results show that the three textbooks had considerable differences in terms of graphical presentations and that they contained a small percentage of high systematical representations. On integration of graphics with text, each textbook was found to be unique. Based on the results of this study, some recommendations are provided for visual representation in physics textbooks so as to enhance the effectiveness of textbooks on teaching and learning, such as highlighting physical and semantic integration of text with graphics.

DOI: 10.1103/PhysRevPhysEducRes.18.020138

I. INTRODUCTION

Textbooks are ubiquitous in education and are considered as major sources of information in teaching and learning. Although various types of teaching and learning resources have become available in recent years, teachers tend to rely heavily on textbooks [1]. Textbooks are a useful tool for teachers, especially for inexperienced teachers, since they provide guidance on how to plan and teach lessons [2]. For students, textbooks are not only a valuable source of knowledge [3], but also have significant impacts on their cognitive and metacognitive skills [4]. Therefore, textbooks have received considerable attention from scholars in science education in general and physics education in particular [5–10].

Text and graphics are two crucial representations of content knowledge in physics textbooks. Text can be used to clarify the meaning of knowledge, but it may not be easy to convey some complex concepts and abstract principles. As a visual representation of knowledge, graphics can be used to facilitate students' understanding and retention of abstract texts [11]. There are a variety of graphics that have different characteristics and thus can serve different teaching purposes. Vekiri classifies visual representations into *non-notational representations* (e.g., photographs, paintings, drawings, and pictures) and *notational representations* (e.g., diagrams, maps, graphs, and charts) [12]. Non-notational representations provide a complex, polysemantic view of mimic reality [13], which can visually present physical phenomena in life and improve students' interest in learning. Contrastingly, notational representations seek to reduce reality in some way to produce a one-to-one correspondence between elements and their referents [12,13]. Notational representations can make physical principles and laws more accessible and stimulate higher-level cognitive processes for students. In a similar vein, Dimopoulos and colleagues suggested that graphics can be categorized into *realistic* and *conventional*: the former displays objects or phenomena in ways close to how they are perceived by human vision while the later makes use of symbols for abstract entities and other conventions used in physics [14]. A transition in history has been observed from the use of mainly realistic images to an increased use of conventional images [5,11].

Visual representations rarely appear in textbooks on their own, but are often integrated with text. According to Peeck, graphics are "not as mere adjuncts to the predominant text" (p. 230), instead, they can serve as important sources of information upon the condition that "the information they

[*]Corresponding author.
bingwei@um.edu.mo

convey is adequately extracted and interpreted" (p. 230) [15]. The physical and semantic integration between graphics and text has been persistently concerned by educational and psychological scholars [16–19] in that it is closely related with the effectiveness of virtual representation in students' learning. Therefore, it is necessary to explore how graphics and text are integrated in physics textbooks used in school. Given the important role played by virtual presentation in teaching and learning, it is expected that graphics are well integrated with the corresponding text in physics textbooks. The greater the integration level, the easier it is for students to make connections between the two subsystems, thereby improving their memory and understanding of the information [20]. However, so far, no empirical evidence has been available concerning the realistic status of the integration of graphics with the text in physics textbooks. This is the main reason that we intended to conduct the present study.

International large-scale assessments, including the Program for International Student Assessment (PISA) and the Trends in International Mathematics and Science Study (TIMSS), have consistently demonstrated that Chinese and Singaporean students performed very well in science. For example, in PISA 2018, four Chinese regions ranked first in science, and Singapore ranked second [21], and in the TIMSS 2019, Singapore's eighth graders ranked first in science among 72 countries and territories [22]. Optics is one of the most challenging topics in introductory physics [23], involving a lot of abstract and complex concepts, which usually makes school students hard to comprehend and even leads to misconceptions for them [24,25]. In order to assist students in understanding optical concepts and principles, physics textbooks often provide an abundance of visual graphics. Based on these considerations, we focused on three junior secondary physics textbooks widely used in China and Singapore with the purpose of exploring two aspects of visual representation in the optical content, presentation of graphics, and integration of graphics with corresponding text. Correspondingly, the two research questions are proposed as follows:

(i) How are graphics presented in the optical content of the three physics textbooks?
(ii) How are graphics integrated with text in the optical content of the three physics textbooks?

II. GRAPHICAL ANALYSIS PROTOCOL

Given the importance of graphics in science textbooks, many are interested in investigating the types of graphics in science textbooks [11,14,26]. The graphical analysis protocol (GAP), developed by Slough *et al.* [1] and refined by Slough and McTigue [27], is unique in that it focuses on the integration of graphics with corresponding text, and thus has been widely adopted by educational researchers [28–30]. According to Slough *et al.* [1], the development of GAP was guided by four principles, they are (i) graphics should be considered by form and function, (ii) graphics should help a viewer build a mental model of a system, (iii) graphics and texts should be physically integrated, and (iv) graphics and texts should be semantically integrated. The GAP includes three parts ("text," "graphics," and "integration") with a total of eleven indicators under them [27]. In this study, we focused on the latter two and modified the part of "graphics" in two aspects. First, we removed the indicator "color" from the GAP, which examines whether textbook graphics are black and white or colored. Since graphics in the three physics textbooks under study are all in color, this indictor does not make any sense in the present study. Second, the GAP included twelve graphic forms with the aim of "providing an extensive description of the target graphics" (p. 306) [1]. For the purpose of this study, the six-form classification suggested by Moline was adopted [31]. Moreover, a new form, called "general image," [26] was added. The revised GAP is presented in Table I. In what follows, the seven indicators contained in the two aspects, graphics and integration of graphics with text, as well as the categories under each indicator, are explained.

The graphics aspect consists of two indicators that describe graphic forms and their systematicity in physics textbooks.

TABLE I. The revised GAP (adapted from [27]).

Aspects	Indicators	Categories
Graphics	1. Graphic form	Photograph; General image; Simple diagram; Analytic diagram; Process diagram; Structure diagram; Graph
	2. Systematicity	Low; Medium; High
Integration of graphics with text	1. Contiguity	Distal; Facing; Proximal; Direct
	2. Indexical reference	No reference; Text references the graphics
	3. Captions	No captions; Identification; Description; Engagement
	4. Semantic relations	Decorative; Representational; Organizational; Interpretational
	5. Level of connection	Level 1; Level 2; Level3

A. Graphic form

In the revised GAP, graphics are classified into seven categories according to their forms:

Photograph.—describe the surface characteristics of objects, such as color, texture, and shape, in order to stimulate students' perceptions and enhance learning.

General image.—they attempt to mimic the real context, and recreate scenes from experiments or real-life, in addition such images do not include any labels or words [26]. *Cartoon illustrations*, *thought bubble text*, and *computer enhanced photographs* are included in this category.

Simple diagram.—they are regarded as labeled graphics that simplify, generalize, or symbolize objects, something that photographs are unable to do. They are normally drawn by hand, for example, by drawing a straight line with an arrow to represent the path of light.

Analytic diagram.—help us to see inside an object or to understand its internal structure and function. This category of diagrams includes *enlargements*, *exploded diagrams*, *cross section*, and *cutaway.*

Process diagram.—this diagram is used to organize a sequence of events. Among the simplest is a *timeline*, which displays events along a spectrum of equal time units. In addition, *flowcharts* and *storyboards* are also included to represent events in a systematic manner.

Structure diagram.—this diagram is about classifying and comparing the information we have. Just by arranging facts into one of these diagrams we can see a pattern in the information that help us to understand it better [31]. *Trees, webs, tables*, and *Venn diagrams* are all examples of structure diagrams.

Graph.—diagrams that include words, numerals, or symbols for measuring and ranking quantifying information. *Spectral graphs*, *line graphs*, *bar graphs*, *and pie charts* are all included in this category.

B. Systematicity

According to Slough *et al.* [32], systematicity refers to "how well a graphic helps readers build a mental image, typically using conventions such as arrows or labels to depict dynamic processes" (p. 4540). The GAP classifies systematicity into three categories: *Low*: the graphic depicts an isolated unit, not integrated into a larger system. For example, the diagram only uses labels to indicate the parts of the camera, but does not describe how they work, which means it does not involve a description of the dynamic process; *Medium*: the graphic depicts some aspects of a system. For example, the diagram depicts the dynamic process using arrows, but does not explicitly show how the dynamic process changes over time; *High*: the graphic would help viewers build a mental model of a system. For example, the diagram uses three frames of a time series which not only depicts a dynamic process, but also illustrates how that process changes over time [27].

The integration of graphics with text aspect, used to describe the degree of spatial and semantic integration of graphics and text in textbooks, is composed of five indicators.

1. Contiguity

This indicator aims to analyze the spatial relationships between visual representations and the relevant content text. A graphic may fall into one of the four categories. *Distal*: graphic and the relevant content text appear on different pages, and readers have to turn a page to view them; *Facing*: graphic and the relevant content text are not displayed on the same page, but in facing pages; *Proximal*: graphic and the relevant content text appear on the same page, but apart by more than half a page. *Direct*: graphic and the relevant content text are displayed on the same page and closely adjacent to each other.

2. Indexical reference

As indicated by the study conducted by Wang *et al.* [19], spatial proximity increases children's attention to text areas and enhances their recall of knowledge, but does not influence comprehension of knowledge. Therefore, it is not sufficient to have graphics and text integrated spatially, but it is also imperative to provide supporting texts that facilitate semantic integration of graphics and text [18]. Indexical reference serves as a supporting text that can draw students' attention to the graphic at the appropriate time [33]. Representations can be classified into two indexing categories: *Text does not reference the graphic*; *Text references the graphics.*

3. Captions

Peeck argues that supporting texts should not only bring the reader's attention to graphics, but also enable them to understand and interpret graphics correctly [15]. As a supporting text, captions can provide explanations of graphics and facilitate student learning [34]. According to the GAP, captions are classified into four categories: *No captions*; *Identification*: caption identifies the target of the graphic but does not provide details; *Description*: caption provides a description with details and associates the graphic to the main text; *Engagement*: caption actively engages viewer (e.g., asks a question, poses a task).

4. Semantic relations

The semantic relationships between graphics and texts can be expressed through graphical functions, and we adopted Carney and Levin's classification, which classifies graphical functions into four categories [16]. *Decorative*: the graphic just adds an affective component which is irrelevant to the text content and even if it was removed, it would not hinder the understanding of the physical concept. *Representational*: the graphic is closely related to the text, as it reflects part or all of the text, which serves to add concreteness to certain terms or concepts within the text. *Organizational*: the graphic is used to organize or summarize the content of the text, thus adding coherence to the text. *Interpretational*: the graphic is used to visualize abstract physical concepts and principles, thus facilitating comprehension of complex text content and improving cognitive abilities.

5. Level of connection

The GAP also analyzes whether the graphic adds new information that is not included in the text. For instance, if a graphic (with captions and labels) describes the text content while adding new information that is not contained in the text, the graphic is considered a connected graphic, and the level of connection is further examined. *Level 1*: the graphic is easy to interpret, and the new information contained in the graphic is clearly linked to the textual content; *Level 2*: the graphic is relatively easy to interpret, and the connection between new information and textual content is less concrete, requiring the reader to draw inferences in order to understand the new information; *Level 3*: the graphic provides new information that requires specific background knowledge and scrutiny in order to fully comprehend.

III. RESEARCH METHOD

Content analysis is a research approach for making replicable and valid inference from texts to the contexts of their use [35]. According to Stemler [36], content analysis can be used with a wide variety of data sources, including textual data, graphic stimuli (e.g., photographs, videos), and audio data. The current study took this approach to examine graphic representation of optical content in the three physics textbooks commonly used in junior secondary school in China and Singapore to understand how graphics are presented and how they are integrated with text.

A. Data sources

Three mainstream junior secondary physics textbooks from China and Singapore provided data sources for this study. Two of them are from China: one was published by People's Education Press (PEP) [37], which is widely adopted across the country, and the other published by Shanghai Science and Technology Publishers (SSTP) [38], which is popular in east China representing regional physics textbooks. Both of which were compiled under the guidance of the national physics curriculum standards [39]. These two physics textbooks are written for 8th grade students (approximately 14 years old) and contain the optical content in a chapter. The physics textbook from Singapore was published by Marshall Cavendish Education (MCE), one of the famous textbook publishers in the country. Unlike the two textbooks from China that are prepared specifically for the 8th grade, the Singapore's textbook is written for the whole lower stage of secondary schooling. And the optical content appears in Chapter 12 of this book [40]. The basic information of physics textbooks involved in this study is presented in Table II.

B. Unit of analysis

According to Krippendorff [35], unit of analysis is an important aspect of the content analysis approach. In this study, the unit of analysis was defined as individual graphics related to the optical content in the three physics textbooks. Since the study focused on the pedagogical function of graphic representation, all graphics within the main text of the optical content were examined, except for those found in the extended content, summary, and exercise sections. Additionally, due to the differences in the content arrangements among the three textbooks, some individual lessons that were not commonly found in them were excluded to ensure the comparison reasonable. As a result, 115 graphics were selected and served as the unit of analysis, including 40 from PEP, 34 from SSTP, and 41 from MCE.

C. Coding process

The coding process was based on the revised GAP with a focus on the two aspects, graphics and integration of graphics with text (see Table I). For each aspect, the coding

TABLE II. The basic information of physics textbooks under study.

Textbook (Year)	Authors	Title	Chapter
PEP (2012)	Peng, Q.C.	Compulsory Education Textbooks: Physics (8th grade)	Chapter 4. The phenomenon of light (Lessons 2–4) Chapter 5. Lens and its application (Lessons 1–4)
SSTP (2012)	Liao, B.Q., and He, R. W.	Compulsory Education Textbooks: Physics (8th grade)	Chapter 4. Colorful light (Lessons 1–3, 5–6)
MCE (2013)	Chew, C., Foong, C. and Tiong, H.	Physics matters	Chapter 12. Light (Lessons 1, 2, 4, 5)

TABLE III. The graphic forms used in three textbooks.

	Non-notational representations		Notational representations				
	Photograph	General image	Simple diagram	Analytic diagram	Process diagram	Structure diagram	Graph
PEP	30.0%	15.0%	42.5%	5.0%	0	7.5%	0
SSTP	44.1%	17.6%	29.5%	5.9%	0	2.9%	0
MCE	21.9%	9.8%	46.4%	2.4%	7.3%	9.8%	2.4%

work was done with its indicators and corresponding categories (see Table I). To promote the reliability of the coding, 30 graphics were randomly selected and coded by the first two authors as a pilot study. A couple of dilemmas were encountered in the coding process. The first dilemma was about the classification of graphical forms: some of the graphics in physics textbooks contained more than one type of graphic. For this case, we adopted Guo's approach [41], which "defines primary types through identification of the clearest prominent feature that are most likely to attract students' attention" (p. 26). An example would be a graphic depicting the phenomenon that light is reflected on the surface of a book, accompanied by a photograph of the book. Since we are concerned mostly with the propagation path of light rather than that of the book itself, we took it as "simple diagram" instead of "photograph."

A second dilemma was encountered when coding the functions of graphics. According to Carney and Levin [16], the conventional functions of graphics can be divided into four categories: decorative, representational, organizational, and interpretational. However, the preliminary analysis found that graphics sometimes may contain more than one function. For instance, a simple diagram can serve as both a representative and interpretive functions. In this case, we determined the most important function based on the textual content associated with it, and coded it accordingly.

Based on the pilot study, where a couple of dilemmas were identified and resolved, the 115 graphics were independently coded by two raters (the first two authors). According to the rater's coding for the seven indicators, "graphic form," "systematicity," "contiguity," "indexical reference," "captions," "semantic relations," and "level of connection" (see Table I), the corresponding kappa values were calculated to be 0.939, 0.956, 0.956, 0.973, 0.930, 0.895, and 0.904. The kappa values were all over 0.8, indicating that the coding was almost perfect agreement [42]. Any coding disputes were discussed by the two raters to reach a final consensus. The coding data was converted to frequencies and percentages, which was used to answer the two research questions.

IV. RESULTS AND DISCUSSION

A. Graphics

To answer the first research question, individual graphics were analyzed in terms of *Graphic form* and *Systematicity*. The results of the graphic form analysis are displayed in Table III. In the PEP, the notational (45%) and non-notational (55%) representations were almost evenly distributed. With the percentage of 61%, the SSTP used more non-notational representations (i.e., photograph and general image). This provided students with a sense of authenticity as the photographs and general images truthfully reflected the relevant contexts in daily life. In contrast with the preference for using non-notational representations in SSTP, 68.3% of representations in MCE were notational. The simple diagram was the most common graphic form in MCE (46.4%) and PEP (42.5%), while the photograph was most frequently used in SSTP (44.1%). Compared with PEP and SSTP, which lack the use of graph and process diagram, MCE employed all seven forms displaying a diversity of graphic forms.

As for *systematicity*, the analysis results (see Fig. 1) revealed a high percentage of low systematical representations in all three textbooks (57.5%, 61.7%, and 51.2% for PEP, SSTP, and MCE). This was caused by the extensive use of isolated pictures. A lot of graphics in the three textbooks, especially in SSTP, only depicted different isolated phenomena that appeared in daily life or laboratory, which were not integrated into a larger system. Optical path diagrams are the typical medium systematical representations in this study as they show the direction and path of light propagation. MCE used many optical path diagrams resulting in its relatively high percentage of medium systematical representations (41.5%). In all three textbooks, high systematical representations only account for

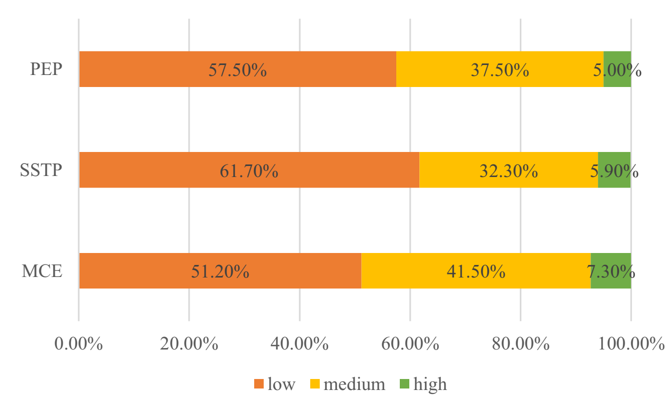

FIG. 1. The representation systematicity of three textbooks.

TABLE IV. Overall contiguity in three textbooks.

	Direct	Proximal	Facing	Distal
PEP	90.0%	0	0	10.0%
SSTP	94.1%	0	5.9%	0
MCE	97.5%	0	2.5%	0

TABLE V. Captions in three textbooks.

	No captions	Identification	Description	Engagement
PEP	27.5%	45.0%	22.5%	5.0%
SSTP	0	94.2%	2.9%	2.9%
MCE	19.5%	26.8%	46.3%	7.4%

a small proportion (5.0%, 5.9%, and 7.3% for PEP, SSTP, and MCE).

B. Integration

To address the second research question, the integration analysis was conducted with five indicators (i.e., contiguity, Indexical reference, captions, semantic relations, and level of connection). As explained earlier, contiguity concerns the spatial relationships between graphic representations and the relevant content text. As shown in Table IV, most graphics were contiguous with the accompanying text, with *direct* accounting for over 90% of the graphics in all three textbooks (90.0%, 94.1%, and 97.5% for PEP, SSTP, and MCE). While the rest in SSTP (5.9%) and MCE (2.5%) were displayed on *facing* pages, 10% of graphics in PEP were *distal* to the text, which means readers have to turn to a new page to view them.

The indexical reference analysis revealed how the text reference the graphics in three textbooks (see Fig. 2). The results underscored the high percentage of referenced graphics in PEP (97.5%) and SSTP (97.1%), whereas the referenced graphics in MCE (54.9%) were relatively less.

A caption is a summary of the content of a graphic, and an appropriate caption would facilitate readers to make an integration of text and image resources [43]. As presented in Table V, a small percentage of captions provided descriptions or tried to engage viewers in PEP and SSTP. Especially in SSTP, 94.2% of captions only identified the target of the graphic but did not provide details, and only 5.8% of captions with descriptions or engagement. By contrast, there were relatively more description (46.3%) and engagement (7.4%) captions in MCE. Furthermore, 27.5% and 19.5% of graphics in PEP and SSTP, respectively, had no captions, which might create problems in understanding the graphics.

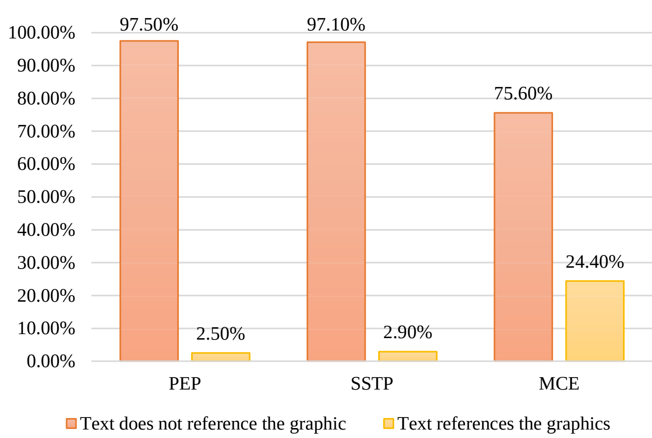

FIG. 2. Indexical reference in three textbooks.

Table VI shows the semantic relationships between graphics and related text (i.e., graphical functions) in three textbooks. The decorative graphics, which just add an affective component, are unlikely to enhance desired outcomes related to understanding, remembering, or applying the text content [16]. Although the side columns used for decoration have been excluded from the statistics, there were still some decorative graphics that can be observed in three textbooks (5.0%, 5.8%, and 2.4% for PEP, SSTP, and MCE). The representational graphic, which can reflect the texts' meaning [41], was the most commonly used in all kinds of textbooks [28,29,32]. It is thus expected to see that the representational graphs accounted for the majority in the three textbooks (65.0%, 64.7%, and 53.6% for PEP, SSTP, and MCE) in this study. Compared with PEP (7.5%) and SSTP (2.9%), both of which are commonly used in China, MCE contained the most organizational graphics (14.6%). A possible explanation is that we encoded tables as organizational graphics, and MCE contains more tables than PEP and SSTP. Moreover, MCE (34.1%) used more interpretational graphics compared with PEP (25.0%) and SSTP (26.6%).

As mentioned earlier, a graphic is considered connective when it not only embodies the information in the text, but also adds new information that is not in the text. The descriptive statistics of graphic connectivity in three textbooks were presented in Table VII. There were some connection graphics in all three textbooks (16, 16, and 23 in PEP, SSTP, and MCE). As the graphics in PEP were usually companied with detailed textual explanations, the percentage of connection graphics in PEP (40%) was the least, compared with the 47% and 56% in SSTP and MCE. The graphical comprehension ability for students who read MCE was highly required as its graphics contained more information that does not appear in the text. This makes

TABLE VI. Overall semantic relationships in three textbooks.

	Decorative	Representational	Organizational	Interpretational
PEP	5.0%	65.0%	7.5%	25.0%
SSTP	5.8%	64.7%	2.9%	26.6%
MCE	2.4%	53.6%	14.6%	34.1%

TABLE VII. Overall connections in three textbooks.

	Counts	Percentages of graphics with connections	Level 1	Level 2	Level 3
PEP	16	40.0%	14 (87.5%)	2 (12.5%)	0
SSTP	16	47.0%	11 (68.8%)	5 (31.2%)	0
MCE	23	56.0%	20 (87.0%)	0	3 (13.0%)

students have to discover parts of new information for getting a better understanding of the conveyed knowledge. As for the levels of connections, most of the connection graphics in PEP (87.5%) and MCE (87.0%) were at level 1, which were easy for students to link the texts with the graphic. While level 1 connection accounted for 68.8%, the percentage of level 2 connection is 31.2% in SSTP. This means students have to reason more to connect the new information contained in the graphics with the related text in SSTP. MCE used a small percentage of level 3 connections (13%), which requires students to have the corresponding specific background knowledge to fully comprehend the new information included in the graphics.

V. DISCUSSION AND IMPLICATIONS

The purpose of this study was to examine graphic representation of optical content in three physics textbooks commonly used in China and Singapore in terms of both presentation of graphics and integration of graphics with text. The results indicate that each textbook has its own characteristics while they share some similarities with regard to presentation of graphics. On the one hand, the three textbooks under analysis have considerable differences with regard to graphic forms. While PEP contains a balanced inclusion of notational and non-notational representations, SSTP is dominated by non-notational representations and MCE is dominated by notational representations. In addition, MCE contains the greatest variety of graphics forms, which might be helpful to achieve different learning aims. For example, when explaining the principle of planar mirror imaging, MCE starts from physical phenomena and uses process diagram to clarify the order of drawing a light path diagram facilitating students to understand the essence of planar mirror imaging, while SSTP and PEP lack such graphics. On the other hand, a commonality among the three physics textbooks is reflected in the systematicity indicator, showing that they all contain a relatively small percentage of high systematical representations. That is to say, graphics are primarily used to describe a single physics concept, rather than placing the physics concept as part of a system in a larger context.

As for the integration of graphics and text in the three physics textbooks, we focused on five indicators. The results showed that the three textbooks differed on each of these indicators. In terms of continuity, SSTP and MCE performed better than PEP since most of the graphics and text in the former two are adjacent to each other. However, all three textbooks still contain some graphics that are far from the text, which may not be conducive to student learning. As for indexical reference, most of the graphics in PEP and SSTP contain indexical references, whereas more than a quarter of those in the MCE do not, which would cause students to have difficulty associating graphics with relevant text, thus increasing extraneous cognitive load [44]. In terms of captions, descriptive and engaging captions dominate in MCE, while identifying captions are most prevalent in SSTP; some graphics in PEP and MCE do not have captions. The analysis of graphic functions suggests that most graphics in three textbooks are used to support students' understanding of physics concepts. Moreover, MCE contains more interpretational graphics, indicating a greater emphasis on using graphics to explain physics principles and laws. For example, when illustrating the phenomenon of a wooden pole bending in water, it is stated in the MCE textbook: "*it appears to be bent because the reflected light from the immersed part of the rod refracts when it travels from water to air*" [40]. If only with these texts, it would be hard for students to make sense of the phenomenon. Thus, an interpretational graphic was used in MCE textbook to show the path of light, illustrating graphicly how the wooden pole would appear bent [40]. Obviously, this can facilitate students' understanding of how refraction works. In terms of the level of connection, MCE owns the highest percentage of connected graphics, with a small number of graphics connectivity at level 3, meaning that only students with relevant background knowledge could understand the meaning of the new information. In contrast, PEP and SSTP contain a relatively low proportion of connected graphics because their text narratives are more detailed and the graphics contain a relatively small amount of new information.

Based on the findings of this study, we would provide several recommendations for selecting and designing graphic representations in physics textbooks with the purpose of maximizing their effectiveness in physics teaching and learning. First, as described earlier, there are various forms of graphics and each one has its own characteristics. The same physics content can be presented in a different way, which may result in different effects. This means that it is necessary to choose an appropriate form of graphics according to the particular educational purpose. For example, when demonstrating the convergence of light by a convex lens, a photograph may be more effective as it maximizes the reproduction of reality and demonstrates the physical phenomenon. When introducing the imaging principle of a projector, however, it would be wise to use a simple diagram because it allows students to focus on the path of light propagation to better understand the principles of physics.

Second, more concern should be given to the systematicity of graphic representations. According to Renkl and Scheiter [45], a high or medium systematical representation often uses a sequence of multiple static pictures that are simultaneously or successively presented or adds motion arrows to a single picture depicting a dynamic process. It has been demonstrated that using these static graphic representations to describe dynamic processes can enhance learning more effectively than using dynamic graphic representations such as animations, simulations, and videos [46]. However, many studies had indicated that school textbooks usually contain a low percentage of high systematical representations [1,29,32], which was confirmed by the present study. Accordingly, we suggest that textbooks should include more high representations. Furthermore, the use of static graphics to illustrate dynamic systems can also be challenging for students as they may not be able to comprehend what is being shown [47]. As such, teachers should provide extra guidance to students regarding how to interpret the information in the graphics.

Third, more attention should be paid to the physical integration of text and graphics. Studies have shown that learning would be enhanced when the text and related graphics are presented together and in close proximity on the same page [48,49]. In this study, however, it has been found that there are still a few graphics (10.0%) located at the distal end of the text in PEP (see Table IV). The cognitive load theory suggests that when graphic and textual information are separated physically, students are forced to turn the page in order to locate the relevant information [50]. Because limited cognitive resources of students, the separation of graphic information and text may increase the unnecessary search process and reduce the resources available for learning process [51,52]. As such, it is recommended that the graphics should be as close to the corresponding text as possible to minimize the extraneous cognitive load on students.

Last but not least, the semantic integration of graphics and text should be highlighted when designing physics textbooks. According to Hannus and Hyönä [53], children spent only 6% of their study time inspecting graphics while reading science textbooks. Researchers have identified specific cues in the verbal text, such as captions, labels, and indexical references, which are helpful to direct students' attention to the graphics and facilitate their comprehension of the text [1,45]. As one of the supporting text, extended captions have been found to facilitate the integration of graphics and text semantically [18,30,43]. A reasonable explanation is that they can direct students towards observing particular details of graphic representations or using them to accomplish specific instructions, such as asking a question and posing a task, rather than simply providing a general description of what is displayed [15]. We therefore suggest that textbook designers should appropriately increase the percentages of descriptive and engaging captions so as to guide students to focus on the details of the graphics and extract the important information from them.

Regarding the function of graphics, it has been found in this study that representational, organizational, and interpretive graphics dominate three physics textbooks under analysis. According to Levin and Mayer [54], these three types of graphics that can facilitate learning by making text more concrete, coherent, and comprehensible. It is worth noting that representational graphics are by no means just redundant of the textual content; when analyzing the three textbooks, we found that some representational graphics were coded as connection graphics as well, meaning that these graphics contained new information that was not present in the text. New information can broaden students' horizons but it may require prior knowledge to understand the graphics better [47]. Therefore, it is imperative that the graphics should be designed based on the life experiences that students already have. Also, there are still a few decorative graphics in the three textbooks. Mayer [48] argues that if the graphics do not relate to the text, they may increase the cognitive load of students. For this reason, such graphics should be avoided whenever possible in the future.

[1] S. Slough, E. McTigue, S. Kim, and S. Jennings, Science textbooks' use of graphical representation: A descriptive analysis of four sixth grade science texts, Reading psychology **31**, 301 (2010).

[2] F. Ogan-Bekiroglu, To what degree do the currently used physics textbooks meet the expectations?, J. Sci. Teach. Educ. **18**, 599 (2007).

[3] I. Devetak and J. Vogrinc, The criteria for evaluating the quality of the science textbooks, *Critical Analysis of Science Textbooks* (Springer, Dordrecht, 2013), pp. 3–15.

[4] H. Akcay, H. O. Kapici, and B. Akcay, Analysis of the representations in Turkish middle school science textbooks from 2002 to 2017, Participatory Educ. Res. **7**, 192 (2020).

[5] B. Bungum, Textbook images: How do they invite students into physics?, Phys. Educ. **48**, 648 (2013).
[6] S. Gumilar, D. Hadianto, I. F. Amalia, and A. Ismail, The portrayal of women in Indonesian national physics textbooks: A textual analysis, Int. J. Sci. Educ. **44**, 416 (2022).
[7] Y. Liu and M. S. Khine, Content analysis of the diagrammatic representations of primary science textbooks, Eurasia J. Math. Sci. Technol. Educ. **12**, 1937 (2016).
[8] C. Ruggieri, Students' use and perception of textbooks and online resources in introductory physics, Phys. Rev. Phys. Educ. Res. **16**, 020123 (2020).
[9] K. S. Serbin, M. Wawro, and R. Storms, Characterizations of student, instructor, and textbook discourse related to basis and change of basis in quantum mechanics, Phys. Rev. Phys. Educ. Res. **17**, 010140 (2021).
[10] C. L. Wong and H. E. Chu, The conceptual elements of multiple representations: A study of textbooks' representations of electric current, *Multiple Representations in Physics Education* (Springer, Cham, 2017), pp. 183-206.
[11] B. Bungum, Images of physics: An explorative study of the changing character of graphic images in Norwegian physics textbooks, Nordic Studies Sci. Educ. **4**, 132 (2008).
[12] I. Vekiri, What is the value of graphical displays in learning?, Educ. Psychol. Rev. **14**, 261 (2002).
[13] J. M. Coleman and J. A. Dantzler, The frequency and type of graphical representations in science trade books for children, J. Graphic Literacy **35**, 24 (2016).
[14] K. Dimopoulos, V. Koulaidis, and S. Sklaveniti, Towards an analysis of graphic images in school science textbooks and press articles about science and technology, Res. Sci. Educ. **33**, 189 (2003).
[15] J. Peeck, Increasing picture effects in learning from illustrated text, Learning Instr. **3**, 227 (1993).
[16] R. N. Carney and J. R. Levin, Pictorial illustrations still improve students' learning from text, Educ. Psychol. Rev. **14**, 5 (2002).
[17] M. Hegarty, P. A. Carpenter, and M. A. Just, Diagrams in the comprehension of scientific texts, *Handbook of Reading Research (Vol. 2)* (Erlbaum, Hillsdale, NJ, 1996), pp. 641–668.
[18] E. M. McTigue and S. W. Slough, Student-accessible science texts: Elements of design, Reading Psychology **31**, 213 (2010).
[19] F. Wang, X. Yang, Y. Fan, and X. Hu, How spatial contiguity influence 7-and 9-year-old children's text-picture reading: Evidence from eye-movement, Studies Psychol. Behav. **18**, 503 (2020), in Chinese.
[20] D. Guo, S. Zhang, K. L. Wright, and E. M. McTigue, Do you get the picture? A meta-analysis of the effect of graphics on reading comprehension, AERA Open **6** (2020).
[21] OECD, *PISA 2018 Results (Volume I): What Students Know, and Can Do* (PISA, OECD Publishing, Paris, 2019), 10.1787/5f07c754-en
[22] IEA, TIMSS 2019 International Results in Mathematics, and Science (2020), https://www.iea.nl/publications/study-reports/international-reports-iea-studies/timss-2019-international-report.
[23] T. Mzoughi, S. D. Herring, J. T. Foley, M. J. Morris, and P. J. Gilbert, WebTOP: A 3D interactive system for teaching and learning optics, Computers Educ. **49**, 110 (2007).
[24] P. Colin, F. O. Chauvet, and L. Viennot, Reading images in optics: Students' difficulties and teachers' views, Int. J. Sci. Educ. **24**, 313 (2002).
[25] A. Widiyatmoko and K. Shimizu, Literature review of factors contributing to students' misconceptions in light and optical instruments, Int. J. Environ. Sci. Educ. **13**, 853 (2018).
[26] D. Guo, K. L. Wright, and E. M. McTigue, A content analysis of graphics in elementary school textbooks, Elem. School J. **119**, 244 (2018).
[27] S. W. Slough and E. McTigue, Development of the graphical analysis protocol (GAP) for eliciting the graphical demands of science textbooks, *Critical Analysis of Science Textbooks* (Springer, Dordrecht 2013), pp. 17–30.
[28] J. M. Nyachwaya and M. Gillaspie, Features of representations in general chemistry textbooks: A peek through the lens of the cognitive load theory, Chem. Educ. Res. Pract. **17**, 58 (2016).
[29] K. L. Wright, E. M. McTigue, Z. R. Eslami, and D. Reynolds, More than just eye-catching: Evaluating graphic quality in middle school English language learners' science textbooks, J. Curriculum Instr. **8**, 89 (2014).
[30] M. S. Khine and Y. Liu, Descriptive analysis of the graphic representations of science textbooks, Eur. J. STEM Educ. **2**, 6 (2017).
[31] S. Moline, *I See What You Mean: Graphic Literacy K-8* (Stenhouse Publishers, Portland, 2012).
[32] S. Slough, B. Cavlazoglu, N. Erdogan, and O. Akgun, Descriptive analysis of a sixth-grade Turkish science text with recommendations for development of future e-resources for multi-touch tablets, in *Proceedings of the Society for Information Technology & Teacher Education International Conference*, edited by P. Resta (AACE, Chesapeake, VA, 2012), pp. 4537–4542.
[33] L. Pozzer-Ardenghi and W. M. Roth, Making sense of photographs, Sci. Educ. **89**, 219 (2005).
[34] L. L. Pozzer and W. M. Roth, Prevalence, function, and structure of photographs in high school biology, J. Res. Sci. Teach. **40**, 1089 (2003).
[35] K. Krippendorff, *Content Analysis: An Introduction to its Methodology* (Sage Publications, Thousand Oaks, CA, 2018).
[36] S. E. Stemler, Content analysis. Emerging trends in the social and behavioral sciences: An Interdisciplinary, Searchable, and Linkable Resource (2015), pp. 1–14.
[37] Q. C. Peng, *Compulsory Education Textbooks-Physics (8^{th} grade)* (People's Education Press, Beijing, 2012), in Chinese.
[38] B. Q. Liao and R. W. He, *Compulsory Education Textbooks-Physics (8^{th} grade)* (Shanghai Science and Technology Publishers, Shanghai, 2012), in Chinese.
[39] Ministry of Education (MoE), *The Compulsory Education Physics Curriculum Standards (2011 version)* (Beijing Normal University Press, Beijing, 2011), in Chinese.
[40] C. Chew, C. Foong, and H. Tiong, *Physics matters* (Marshall Cavendish Education, Singapore, 2013).

[41] D. Guo, The impact of graphic graphics on K-12 student learning across disciplines, Ph.D. thesis, Texas A & M University, College Station, Texas, 2018.

[42] A. J. Viera and J. M. Garrett, Understanding interobserver agreement: The kappa statistic, Fam. Med. **37**, 360 (2005).

[43] R. M. Bernard, Using extended captions to improve learning from instructional illustrations, Br. J. Educ. Technol. **21**, 215 (1990).

[44] M. P. Cook, Graphic representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles, Sci. Educ. **90**, 1073 (2006).

[45] A. Renkl and K. Scheiter, Studying graphic displays: How to instructionally support learning, Educ. Psychol. Rev. **29**, 599 (2017).

[46] B. Imhof, K. Scheiter, J. Edelmann, and P. Gerjets, How temporal and spatial aspects of presenting visualizations affect learning about locomotion patterns, Learning Instr. **22**, 193 (2012).

[47] M. Cook, Students' comprehension of science concepts depicted in textbook illustrations, Elect. J. Res. Sci. Math. Educ. **12**, 1 (2008).

[48] R. E. Mayer, Multimedia learning, *Psychology of Learning and Motivation* (Academic Press, New York, 2002), Vol. 41, pp. 85–139.

[49] R. Moreno and R. E. Mayer, Cognitive principles of multimedia learning: The role of modality and contiguity, J. Educ. Psychol. **91**, 358 (1999).

[50] R. E. Mayer, *The Cambridge Handbook Of Multimedia Learning* (Cambridge University Press, Cambridge, England, 2005).

[51] P. Ayres and J. Sweller, The split-attention principle in multimedia learning, *The Cambridge Handbook Of Multimedia Learning* (Cambridge University Press, Cambridge, England, 2005), pp. 135–146.

[52] P. Chandler and J. Sweller, The split-attention effect as a factor in the design of instruction, Br. J. Educ. Psychol. **62**, 233 (1992).

[53] M. Hannus and J. Hyönä, Utilization of illustrations during learning of science textbook passages among low- and high-ability children, Contemp. Educ. Psychol. **24**, 95 (1999).

[54] J. R. Levin and R. E. Mayer, Understanding illustrations in text, *Learning from Textbooks* (Routledge, London, 2012), pp. 105–124.