Multiple Representations in Physics and Science Education – Why Should We Use Them?

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MULTIPLE REPRESENTATIONS IN PHYSICS EDUCATION

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EXTENDED PREFACE

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This extended preface will provide a summary of each chapter in the book and show how the different authors and their research contributes to the overall agenda to further investigations with multiple representation in physics education. The book comprises a Preface, an Introductory chapter, three chapters with a focus on Multiple Representations as Models And Analogies, five chapters with a Focus On Multiple Representations as Different Multiple Modes, four chapters with a focus on Multiple Representations as Reasoning and Representational Competence.

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Chapter 1

Multiple Representations in Physics Education

Multiple Representations in Physics Education – Why Should We Use Them?

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Keywords

learning with multiple representations, mathematical modelling, multiple representations in physics education, text and picture comprehension, theories on learning with multiple representations.

Introduction

Imagine you are teaching physics at high school and you want to make your students familiar with the concept of block and tackle. Would you do so by just explaining in a verbal fashion, for instance how the length of the pulling rope or the number of strands relates to the pulling force? Probably not – after a demonstration with a real tackle you might most likely show students exemplary pictures of different situations with tackles (cf. Figure 2), point at certain parts of the pictures and by doing so, explaining the concept to your students. In this case, you would already make use of multiple representations - (spoken) words and pictures. The reason for doing so is very obvious. Many concepts, processes or relations can be comprehended much more quickly when some kind of picture is provided because pictures are able to show at once what would take much longer to be described with words or demonstration experiments. Furthermore, students are able to visualize the rather abstract contents of physics topics being taught such as with the block and tackle. Moreover, when using multiple sources of information, learners are able to choose those sources with which they prefer to learn, in this case the real tackle or the pictures.

Another reason for using multiple representations in physics teaching is the structure of physics itself. Physics uses mathematical modelling to describe phenomena and to explain relations between variables. Therefore, teaching and learning physics necessarily includes both the conversion of physics modelling into mathematical modelling (e.g., regarding functional relations) and the interpretation of mathematical models from a physics point of view (cf. Bing & Redish, 2009; Nielsen, Angell, & Grønmo, 2013). Newton's law of gravity, for example, can only be understood and applied to different problems when the functional relation is used in a mathematical form. But for instance in schools, the consequences for the behavior of physical objects and their predictability are often presented verbally. In addition both modes, the verbal and the mathematical, need graphs following mathematical rules but expressing physical meaning.

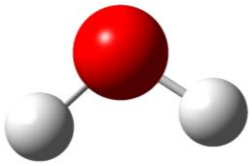
Therefore in physics, more than only one representational format is often used to convey information and support knowledge construction. Accordingly, and developed not only for teaching physics, a number of well-established theories claim that the use of multiple representations can enhance learning. These theories describe the basics of human cognitive architecture, in particular the processing limitations of working memory (e.g., Baddeley, 1992; Paivio, 1986; Sweller, 2010), and consider how instructional materials in general should be designed to support learning (e.g., Ainsworth, 2006; Mayer, 2009; Schnotz, 2005). In this chapter, we will discuss these theories and link them to the "choreographies of teaching" approach by Oser and Baeriswyl (2001), who emphasize the need to distinguish between the sight structure of a learning scenario (e.g., instructional materials in a physics lesson) and the underlying deep structure, which refers to the way in which learners process and comprehend information.

By bringing together these approaches, the readers of this chapter will acquire knowledge on how multiple representations can be used in ways that adhere to common instructional design theories on the presentation side and simultaneously supports deep level understanding on the learners' side. First, however, we will clarify what we actually mean when we talk about "multiple representations".

What Are Multiple Representations?

The term "representation" is used in a very wide fashion in the educational research literature. For instance, one should be aware of whether an *external representation* (such as a text, a graph, or a picture) or an *internal representation* (the mental model a learner builds with regard to a certain learning content) is being described.

In an attempt to classify and unitize representations in chemistry, Gilbert and Treagust (2009) distinguish between three types: a phenomenological or macro type (that is, representations of the empirical properties of compounds), a model or submicro type (external representation, e.g., visual models that depict the (assumed) arrangement of entities, such as atom or molecule models, see Figure 1), and a symbolic type (that is, the submicro type further simplified to symbols, e.g., “Na” or “Cl⁻“, see Figure 2).



(a)

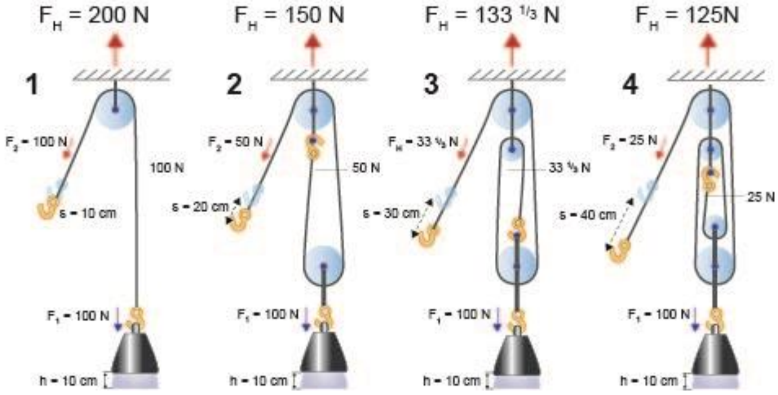
H_2O

H-O-H

(b)

Fig. 1 Example for submicro type representation (a) and symbolic type representations (b) of a water molecule.

While Gilbert and Treagust (2009) use the term “representation” for external, visible representations (such as the ones in Figure 1) as well as for internal representations (comparable to mental models), a remarkable amount of instructional design research that deals with multiple representations refers more or less explicitly to *external* representations, or in other words, any kind of visualizations. For instance, theories such as the *Integrated Model of Text and Picture Comprehension* (ITPC; Schnotz, 2005) or the *Cognitive Theory of Multimedia Learning* (CTML; Mayer, 2005, 2009) focus on a multimedia concept of multiple representations – that is, a combination of textual and pictorial information. With regard to our example of the block and tackle concept, a classical multimedia learning material would for instance include one or more pictures of a block and tackle that are accompanied by explanatory text (Figure 2).



“The mechanical advantage of a block and tackle system is equal to the number of supporting ropes or cables. Notice how the pulling force advantage of a pulley varies depending on the number of strands that it has. If it has a single strand, then the pulling force advantage is 1, which is really not an advantage at all. Two strands give a pulling force advantage of 2, three strands give a pulling force

advantage of 3, and so
forth.”

Fig. 2 Multimedia learning material consisting of text and accompanying pictures for the concept of block and tackle.

A broader view of external multiple representations is given by Ainsworth (1999; 2006). According to her DeFT (Design, Functions, Tasks) taxonomy, learning with multiple representations means that two or more external representations are used simultaneously. This can include the classical text-picture-combinations that are described in the ITPC and the CTML, but also goes a step further by considering any other kind of combinations of external representations as well. For instance, with regard to our block and tackle example, instead of showing the picture with accompanying text, one might also show the text accompanied by a table that systematically lists examples for weights, number of strands, length of ropes and resulting pulling power.

In this regard, a specific form of representation is characteristic especially for physics education, namely mathematical expressions like, for example, equations or functions (cf. Angell., Kind, Henriksen, & Guttersrud, 2008). Generally, mathematical expressions used especially in physics usually describe a system by means of a set of variables and a set of equations that establish relationships between the variables that represent specific properties of the system. For instance, Newton's laws causally describe phenomena of the meso-world. However, looking at micro and macro conditions, quantum mechanics and relativity theory must be used. Another feature of physical modeling is the use of idealized models to reduce influencing variables such as massless or point objects or gas with idealized behavior. The description of such phenomena includes mathematical models, mostly functional relations, such as the above-mentioned Newton's gravity law, Maxwell's equations, or the Schrödinger equation. Such models should thus be taken into account in addition to classical formats of multiple representations such as written text or instructional pictures.

In the following paragraphs, we will describe the ITPC, CTML and DeFT model in greater detail, before we will link their views on learning with *external* multiple representations to the more learner-focused view of *internal* mental representations by Oser and Baeriswyl (2001).

Theories On Learning with Multiple Representations

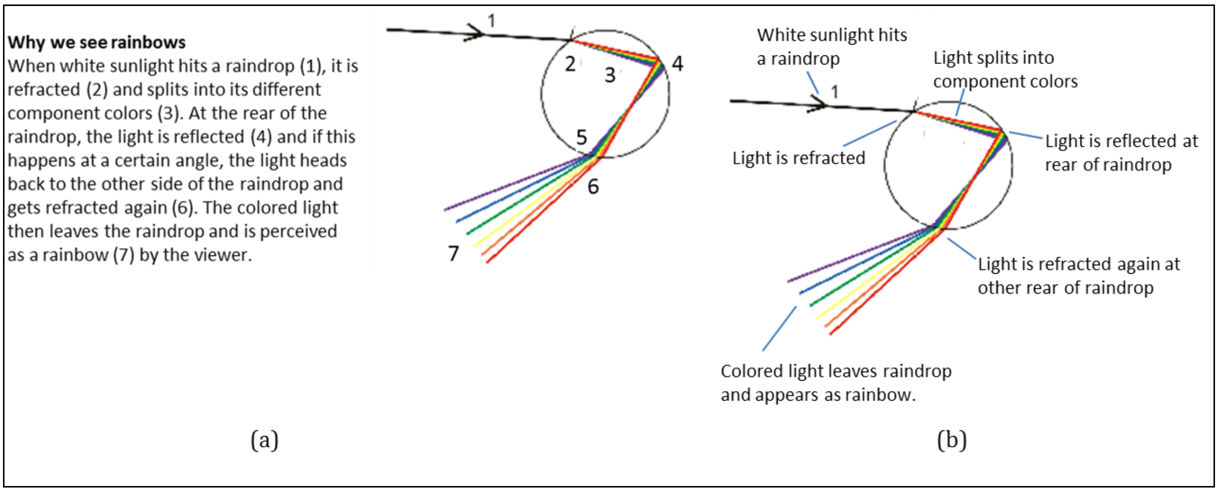
The question of why using multiple representations in instructional materials fosters meaningful learning has been addressed in a remarkable number of studies and led to several well-established theories. Most of these theories are based on assumptions about information processing and the structure of the human mind. More specifically, working memory is assumed to be limited with regard to the amount of information it can process at a certain time (Baddeley, 1992). This information can consist of multiple forms of representations, which are either processed in a verbal/auditory or a visual/pictorial channel (cf., *dual channel assumption*; Paivio, 1986), depending on the modality of the information. Similar to the overall capacity of working memory, both channels are assumed to be limited regarding the amount of information they can process at a time and in parallel. In this regard, it is recommended to make optimal use of both channels instead of overloading only one of them. One way of doing so is to stress both channels by using multiple representations in instructional materials.

The Cognitive Theory of Multimedia Learning (CTML)

Based on this view of information processing, the CTML (Mayer, 2005, 2009) proposes to use multimedia instructional materials to support deep level understanding and thus meaningful learning. As has been mentioned above, the CTML mainly focuses on multiple representations in the sense of text and picture combinations. In this regard, Mayer (2009) states in his *multimedia principle* that “Students learn better from words and pictures than from words alone” (p. 223). This principle is based on the assumption that words and pictures are qualitatively different with regard to the information they contain; and because of the different channels in which they are processed, different information contents are being learned and (when learning takes places optimally) integrated to one coherent mental model. It seems that scientists intuitively apply this idea of picture-supported explanations for more than 4000 years; for example when looking at the more than 4500 years old Egyptian stone carving showing Nut, the queen of the sky, spanning the dome of the sky (Metropolitan Museum, New York) or drawings of Galilei (1610), who illustrated valleys and hills on the moon accompanied by verbal descriptions. The multimedia principle has been proven in several studies using paper-based as well as computer-based instructional materials (e.g., Mayer & Sims, 1994; Plass & Jones, 2005; Schwamborn, Thillmann, Opfermann & Leutner, 2011; for an overview see Mayer, 2009; 2014).

However, just combining words, pictures, mathematical expressions or other kinds of visualizations does not automatically guarantee meaningful learning. The CTML states several further principles that go into more detail with regard to *how* multimedia materials should be presented and combined. For instance, the *modality principle* states that when using text and pictures together, the text should be spoken rather than written, because in this case both the auditory and the visual channel are used instead of overloading the visual channel only. While this principle could be supported in a large number of studies (cf., Ginns, 2005; Mayer, Harskamp & Suhre, 2007), others argue that written text can be as effective given that there is enough time to process both the text and the pictures (e.g., Kalyuga, 2005; Tabbers, Martens & Van Merriënboer, 2004). In this case, written text might even be superior to spoken text, because while the latter is transient in nature, written text can be re-read and scanned for relevant information selectively.

Two less controversial principles that could be shown for auditory as well as for visual multiple representations are the *spatial contiguity principle* and the *temporal contiguity principle*. These principles state that when using multimedia learning materials, the different representations (e.g., the text and pictures as shown in Figure 3) should be presented closely together (Ginns, 2006; Mayer & Fiorella, 2014; Mayer & Moreno, 1998). That is, in textbooks, paragraphs explaining a certain phenomenon should be placed right beside the respective picture. Optimally, text parts might even be integrated into the respective parts of the picture. For instance, when explaining the refraction of light in raindrops when teaching about the emergence of rainbows, learning materials as shown in Figure 3a might be less helpful than the more spatially contiguous presentation in Figure 3b, because in the first case, associated parts of the learning materials are presented far from each other. In this case, *split attention effects* can occur, that is, working memory capacities are stressed with visual search processes that are actually unnecessary and do not contribute to comprehension and learning (Ayres & Sweller, 2005; Kalyuga, Chandler & Sweller, 1999). The same assumption applies to instructional materials that are presented in temporal contiguity – very simply stated, when explaining the concept of block and tackle, the teacher should not talk first and then show the respective picture, but show the picture at the same time as describing the principles depicted there.



Why we see rainbows
When white sunlight hits a raindrop (1), it is refracted (2) and splits into its different component colors (3). At the rear of the raindrop, the light is reflected (4) and if this happens at a certain angle, the light heads back to the other side of the raindrop and gets refracted again (6). The colored light then leaves the raindrop and is perceived as a rainbow (7) by the viewer.

Fig. 3 Examples for learning materials that are spatially separated and might cause split attention (3a) or that adhere to the spatial contiguity principle (3b).

The redundancy principle states that when presenting text and pictures together, using identical written and spoken text at the same time is unnecessary and can even hinder learning, because in this case, the same kind and amount of information is presented and has to be processed twice at a time (Craig, Gholson, & Driscoll, 2002; Mayer, 2009; Sweller, 2005). This double attention to text and pictures stresses the respective working memory channels, but no additional knowledge gains can be expected. However, it should be noted that avoiding redundancy does not mean that the multiple representations used in instructional materials are completely different from each other with regard to the information they contain. In contrast, a certain amount of overlap is necessary so that the relations between the representations (that should all aim at conveying knowledge on one certain topic, model etc.) become clear and support the integration of information and thus the construction of one coherent mental model (Scheiter, Wiebe, & Holsanova, 2008).

The signaling principle (Mayer, 2005, p. 183) states that “people learn better when cues that highlight the organization of the essential material are added” (cf., Mayer & Fiorella, 2014; van Gog, 2014). That is, when using multiple representations such as text plus picture or a table with an accompanying graph, highlighting techniques such as color coding or printing parts of the text in bold or cursively, can off-load working memory and thus free capacities that can be used for meaningful learning. In this case, learners would not have to use these capacities to search for the most relevant information in instructional materials (Harp & Mayer, 1998; Mautone & Mayer, 2001).

Finally, the coherence principle states that despite the benefits of multimedia learning and multiple representations, all materials that do not directly contribute to the comprehension of the content to be learned and are thus extraneous materials should be excluded (Mayer &

Fiorella, 2014). For instance, according to Mayer (2009), text parts and pictures that are interesting, but irrelevant for the actual information processing process should be removed from learning materials, because in this case, working memory capacities are used for paying attention to these unnecessary details, while at the same time, they cannot be used for the construction of schemas, integration of information sources or meaningful learning. Such "seductive details" can even be detrimental for learning when learners are tempted to focus their attention around the wrong kind of information. However, the coherence principle has also led to some controversies in educational research, as it tends to ignore affective variables such as motivation and interest. In this regard, recent research (e.g., Lenzner, Schnotz, & Müller, 2012; Park, Flowerday, & Brünken, 2015) has shown that seductive details such as decorative pictures are not necessarily harmful and can even foster learning, when they are able to induce and thus have an indirect positive impact on learning.

Taken together, according to the CTML, multimedia learning materials and thus the use of multiple representations are recommended because, compared to learning with single representations such as text only, they address different processing channels in working memory, contain information of different kinds and different qualities and support the construction of coherent and integrated mental models. In other words, using multiple representations can foster learning.

The Integrated Model of Text and Picture Comprehension (ITPC)

Very similar to the CTML, the ITPC (Schnotz, 2005, 2014; Ullrich, Schnotz, Horz, McElvany, Schroeder, & Baumert, 2012) also assumes that the processing of multiple representations takes places in two different channels, which are called the auditive and the visual channel. In a first step, all incoming information is processed on a perceptual level (e.g., text-surface representations or visual images). This perceptual level is followed by a cognitive level when information is being processed in working memory in a verbal and/or pictorial channel. Contrary to the CTML, which states that visual and verbal information first lead to the construction of visual and verbal mental models, which are later on integrated into one coherent mental model, the ITPC assumes that this integration and building of one mental model takes place right from the beginning of the processing of multiple representations. That is, information being processed in each of the two channels is aligned and matched from the start of information processing.

In the ITPC, the benefits of learning with multiple representations (in this case, again, primarily with text-picture combinations) are based on this assumption of an integrative processing of verbal and pictorial sources of information; however, an important condition for these benefits to take place is that the respective “verbal and pictorial information are simultaneously available in working memory” (Horz & Schnotz, 2008; p. 50). Only in this case, learners are able to recognize that the different representations belong together and can map them to their respective counterparts to make use of the information contained in both of the sources.

In line with the CTML and the ITPC, the work of Ainsworth (2006, 2014) proposes that learning with multiple representations is not automatically effective, but that these representations should fulfil certain functions. In contrast to the CTML and the ITPC, however, Ainsworth’s view of multiple representations comprises much more than only text-picture combinations. Her framework will be described in greater detail in the following.

The DeFT (Design, Functions, Tasks) Framework for Learning with Multiple External Representations

According to Ainsworth (2014; see also Tsui & Treagust, 2013), learning with multiple representations takes places when any two or more external representations are used in instructional materials. In a classical multimedia view, this can comprise (written or spoken) text and accompanying pictures, but multiple external representations (MERs) can also include photos, diagrams, tables, graphs, concept maps, or even notes taken during learning. In this regard, specific combinations of MERs are not effective in themselves, but they should fulfil certain functions for learning (see Figure 4).

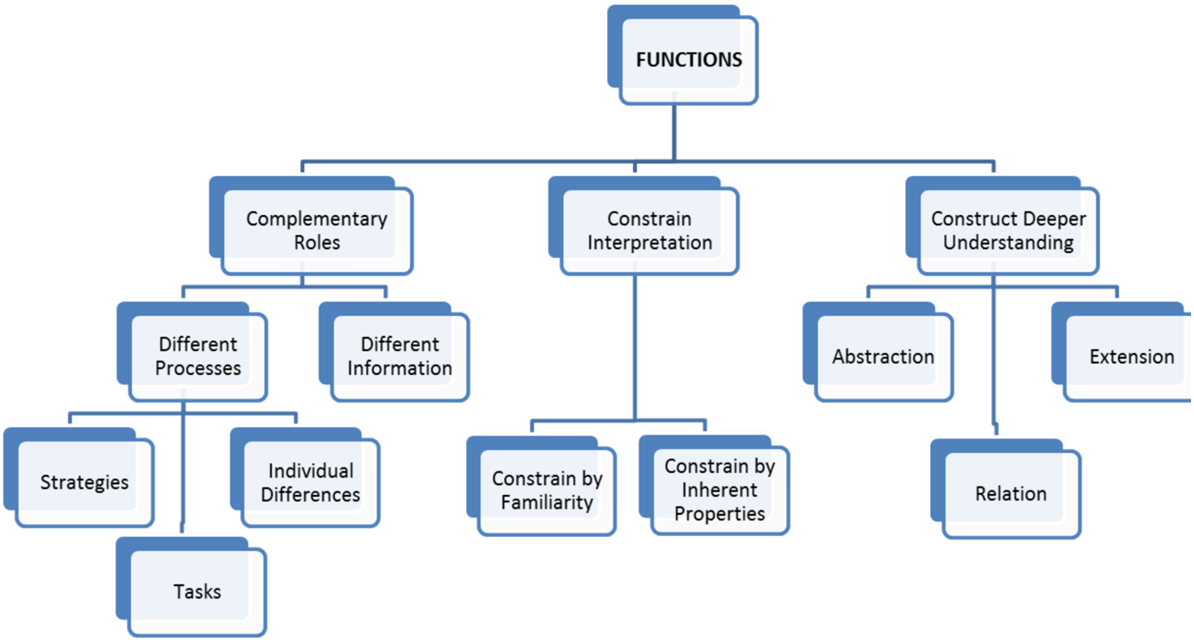


Fig. 4 Functions of multiple external representations according to the DeFT framework (Figure adapted from Ainsworth, 2006).

First, learners can benefit from MERs if the different representations fulfil complementary functions, that is, each of the single representations should at least partly offer unique information or support different inferences (Ainsworth, 2014). In other words, multiple representations support comprehension, when they either contain qualitatively different aspects of the information to be learned, or when they convey the same information, but in different ways. For instance, when the concept of acceleration is taught for rectilinear motion, the teacher could just state or write that constant acceleration can be expressed as the differential quotient of (change in) velocity divided by the time interval, Δt, and could show this quotient along with the formula for acceleration. In addition, the teacher could present a table with exemplary values for the acceleration of a vehicle and depict these values by means of the respective graph (see Figure 5).

Time in seconds	Velocity Car 1	Velocity Car 2
0	0	0
1	4	1
2	8	4
3	12	5
4	16	7

$$a\,(t) = \frac{\Delta\, v}{\Delta\, t}$$

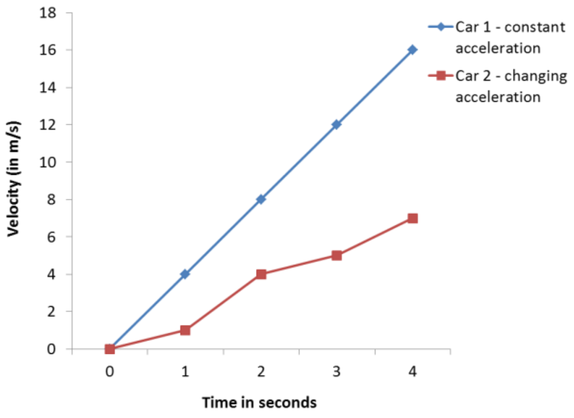


Fig. 5 Example for learning materials on acceleration using multiple external representations.

In Figure 5, the table and the graph actually contain partly the same but, due to different types of representation, also complementary information, in addition generalized by the function a(t). In this case, using multiple representations (that is, presenting all three to the learners) would support the steps of a learning process from changing velocity in time and for rectilinear motion to the notion of acceleration as a general description of a phenomenon. Another advantage of MERs is that they can support different cognitive processes, because individual differences can be taken into account. That is, learners could “choose to work with the representation that best suits their needs” (Ainsworth, 2006, p. 188). Similarly, MERs can foster learning, when learners can choose the representation that best fits the requirements of a certain task – that is, performance is enhanced when the structure of the external representation is similar to the structure of information required to solve the respective problem (cf., Gilmore & Green, 1984). Finally, with regard to different processes, presenting learners with MERs might encourage them to use more than one strategy to solve a problem (Ainsworth & Loizou, 2003; Won, Yoon & Treagust, 2014). For instance, Tabachnek, Koedinger, and Nathan (1994) found that using multiple strategies when being exposed to multiple representations was twice as effective as just using one of the strategies in isolation.

In addition to fulfilling complementary functions by supporting different cognitive processes, MERs can also provide complementary information, that is, the single representations contain (partly) different but complementary aspects of the information. It would be harder or even impossible to learn with one single representation in isolation, for instance, learning about how a block and tackle works would probably be possible with just a written text describing the mechanisms behind and the relations between the number of ropes, position of roles and pulling force. It would, however, be much easier (and learning might take place much quicker) with an accompanying picture (*cf.,* Figure 2), because this picture contains visual / spatial information that can be seen at once, which is not possible to realize in a sequentially organized text. The picture in this case would complement the text by providing additional information.

Besides taking into account that different representations contain complementary information, MERs can also support learning if they constrain each other's interpretation possibilities when being presented together. As can be seen in Figure 4, this can be done in two ways. First, if one representation is significantly more familiar to the learner than the other, this familiar representation can constrain the interpretation of the other one. According to Ainsworth (2006), this is often the case when complex graphs are used in instructional materials. Interpreting these graphs can be challenging for less experienced learners. Consequently, providing a table or a picture or an explanatory text along with the graph would help learners make sense of the data depicted in the graph and thus foster learning. Second, besides familiarity, also inherent properties of the representations can constrain each other's interpretation. For instance, imagine working in a high-class restaurant and having to learn how the cutlery has to be positioned around the plates. Just being told "Put the desert spoon and the cheese fork above the plate; thereby the spoon should be above the fork." might give you some information, but not enough with regard to the directions in which the spoon and fork should point or the distances between plate, fork and spoon. Showing a picture at the same time that depicts a standard cutlery arrangement would immediately constrain the interpretation options for the above instruction. Similarly, the interpretation of descriptive representations can be constrained by presenting them along with a depictive representation (Schnotz, 2014) – for example, the word "force" might lead to very different internal images unless it is accompanied by a picture, such as a pulley with indicated absolute values of pulling and lifting forces and their directions (cf. Figure 2). (For a more fine-grained explanation of descriptive versus depictive representations, see the following sections.)

Finally, the third function of multiple external representations according to the DeFT framework is that such combinations are able to promote a deeper level of understanding. This is the case when learners are able to integrate information from the different representation modes and thus gain knowledge that would be hard to infer from just one representation alone (Ainsworth, 2006). In order for MERs to construct such a deep conceptual understanding, three processes need to be considered. First, learners should be able to *abstract* relevant information from the representations and by doing so, construct references across the multiple representations that represent the underlying structure of a content to be learned. Second, learners should be able to *extend* the knowledge they have with regard to one representation to learning with other representations without fundamentally reorganizing the actual knowledge. For instance, when having learned about Ohm's Law by means of the formula $I = V/R$ (with R=constant and independent of current and voltage) and a graph depicting the electric current as a function of the ratio between voltage and resistance, learners should be able to generalize this knowledge to the comprehension of respective tables or to a related solution of the equation. Third, learners should be able to *relate* representations to each other, that is, they should be able to translate between representations – for instance by being able to draw a graph when the acceleration formula is given along with the table with exemplary values. According to Ainsworth (2006), "this goal of teaching relations between representations can sometimes be an end in itself" (p. 189).

To sum up, multiple external representations according to Ainsworth (2006, 2014) can support learning when they are designed in a way that they (a) support different cognitive processes or include complementary information, (b) constrain interpretation options, thereby preventing inaccurate interpretations and (c) promote deep level understanding by means of abstraction, extension and relation (cf., Tsui & Treagust, 2013). Especially with regard to the third proposed function of MERs, an overlap with the Cognitive Theory of Multimedia Learning and the Integrated Model of Text and Picture Comprehension can be seen in that in all three theories, multiple representations, especially multimedia learning materials, are assumed to be beneficial for learning only if learners are able to recognize that the different representations are meant to convey the same knowledge, and if the learners are able to mentally relate the different sources of information to each other and integrate them with existing knowledge and schemas already stored in long-term memory. However, these benefits of multiple representations depend on the *kind of external representation* (text and/or pictorial representations) used as well as on individual learner characteristics. These aspects are the focus of the next two sections.

Types of External Representations and Their Benefits for Learning

In the previous section, we have described the coherence principle of the CTML (Mayer, 2009; Mayer & Fiorella, 2014), which states that interesting but irrelevant materials should be excluded from learning contents. This already points to one important characteristic of external representations, namely the question, whether they have any instructional value. Although there are newer strains of research that also support the assumption that seductive details such as decorative pictures can be (indirectly) beneficial for learning (Lenzner et al., 2012; Opfermann, Schmeck, Wienand, & Leutner, 2014) because of their motivational potential, we will focus on external representations that are, at least to some degree, instructional, namely, they have some kind of explanatory value. Such representations can be divided into verbal representations such as written or spoken text and pictorial representations such as pictures, graphs, photos or drawings.

Characteristics of Text that Are Beneficial for Learning

When one or more of the multiple external representations used for learning contains text, the obviously most important aspect in this regard is that the text is comprehensible (cf., Leutner, Opfermann, & Schmeck, 2014). To ensure text comprehensibility, Langer, Schulz von Thun and Tausch (2006) introduced the *"Hamburg Approach" for language comprehension*, which proposes four characteristics that written or spoken text should fulfill to foster learning. The first characteristic is *simplicity*, that is, sentences should be formulated concisely, and complicated words and phrases should be avoided whenever possible. Second, with regard to *organization*, text should be clearly arranged, and an internal as well as external structure should be visible. Third, *conciseness* is important in that sentences should be short and not long-winded. Fourth, text should be able to support some kind of *motivational-affective stimulation,* that is, it should be able to arouse the interest of learners. Overall, it is recommended that the longer a text is and the more complex the topic to be learned, the better it is not to present the respective text as a whole, but to split it up in smaller and meaningful units that can be processed consecutively – a suggestion that is also reflected in the segmenting principle of the CTML (Mayer & Pilegard, 2014) or in suggestions on how to offload working memory by optimizing instructional design (cf., *Cognitive Load Theory*; Sweller, Ayres, & Kalyuga, 2011).

Characteristics of Pictorial Representations that are Beneficial for Learning

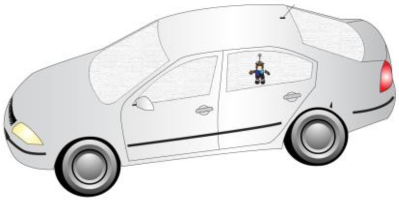
In general, pictorial forms of multiple representations can be found in several facets. For instance, a distinction can be made between static (e.g., pictures, photographs or drawings) and dynamic visualizations (e.g., videos, animations or interactive graphs). In their meta-analysis, Höffler and Leutner (2007) found in this regard that animations are on average superior to static pictures (with a small to medium effect size of d = .37), but that this superiority mainly shows up when the visualizations are very realistic (that is, real videos) or when dynamic contents have to be learned, such as steps of a certain process. For instance, for a learner to *understand how* a block and tackle really works, an animation might be preferable, while a static picture such as the one in Figure 3 would do if the goal was to learn about the relation between ropes, roles and pulling power (see also Höffler, Schmeck, & Opfermann, 2014).

Another distinction that has attracted a considerable amount of recent research refers to the question, whether a visualization such as a picture is presented to the learners along with the other representations such as the text, or whether learners are requested to generate external representations by themselves. In this regard, the *generative drawing principle* (Schwamborn, Mayer, Thillmann, Leopold, & Leutner, 2010; Schmeck, Mayer, Opfermann, Pfeiffer, & Leutner, 2014; for an overview see Leutner & Schmeck, 2014) states that asking learners to draw pictures of the instructional contents themselves while reading a text can enhance learning because it encourages learners to engage in deeper cognitive and metacognitive information processing and thus fosters generative processing. The finding that self-generated drawings can improve learning has been confirmed in several studies (e.g., Ainsworth, 2011; Van Meter & Garner, 2005), but these benefits are also subject to several preconditions such as the quality of the drawing or the question whether instructional support for instance by means of drawing tools is available (cf., Leutner & Schmeck, 2014).

Irrespectively of whether a visualization is static or dynamic and whether it is presented or self-generated, a further distinction can be made following an approach by Schnotz (2005), who distinguishes between descriptive (or propositional) and depictive representations. *Descriptive representations* do not have any structural similarity with the content matter they are supposed to describe and are often used synonymously with symbols (see Figure 7a). For instance, the letter “I” or the word “electric current” do not look like electricity, they are just meant to describe the concept. Similarly, “--⊗--“ does not look like a light bulb, but once a learner is used to this symbol in technical and physics domains, he or she is able to learn and work with it. *Depictive representations,* on the other hand, can be compared more to icons that show similarities or structural commonalities with the respective referent they are supposed to depict. For instance, the drawing of a car is depictive – although not being identical with a real car, it shows enough overlap to be recognized as a car (see Figure 7b).

Car
Automobile
Skoda

(a)



(b)

Figure 7. Examples for descriptive (a) and depictive (b) representations of a car according to Schnotz (2005).

While descriptive representations appear to be more suitable to convey abstract knowledge, depictive representations are informationally more complete (e.g., the drawing or photograph of a car contains more details at one sight than the word “car” or even the more concrete word “Skoda Octavia GreenLine silver”. Concrete knowledge and the drawing of inferences can thus be better supported by providing depictive representations. It has to be noted, however, that this advantage of being informationally more complete can also cause opposite effects when there are too many details that are not needed for learning and that distract learners and stress cognitive capacities that could otherwise be used for meaningful learning (cf., *extraneous cognitive load;* Sweller, Van Merriënboer, & Paas, 1998).

Furthermore, pictorial representations can be classified according to an approach by Niegemann, Domagk, Hessel, Hein, Zupfer and Zobel (2008). The authors distinguish between *realistic pictures* (e.g., the drawing or photograph of a block and tackle such as in Figure 3), *analogy pictures* (e.g., depicting the limited capacity of working memory by means of a bottle that can only be filled to a certain extent until it overflows), and *logical pictures* (such as diagrams and graphs, see Figure 6). With regard to realistic pictures, research has shown that the degree of realism that is beneficial for learning depends upon several factors such as the prior knowledge of learners (Klauer & Leutner, 2012). For instance, a highly realistic picture might overburden learners because - as mentioned in the previous paragraph – there is extraneous load created through the attempt to process all the details that are actually not necessary for comprehension (see also Dwyer, 1978; Rieber, 2000). According to Niegemann et al. (2008), a medium level of realism should be beneficial for learning in most cases.

Analogy pictures (in terms of the assumptions by Schnotz, 2005, these would be descriptive rather than depictive visualizations) do not necessarily show structural similarities with the contents or object that they are supposed to depict on a visual or surface level; however they relate to each other in some kind of analogy relationship (Leutner et al., 2014; Niegemann et al., 2008). Such representations are especially suitable when abstract concepts have to be illustrated – for instance, “electrical energy” is an abstract term and rather a mental model in itself, but it can partly be visualized by using water circuits as done by Paatz, Ryder, Schwedes and Scott (2004). Furthermore, analogy pictures support transfer abilities, given that learners understand that they are learning with analogies (cf. DiSessa, Hammer, Sherin & Kolpakowski, 1991; Glynn, 1991; Leutner et al., 2014).

Finally, logical pictures also do not have structural or obvious similarities with the contents they represent, but they depict these contents schematically. For instance, the graph in Figure 6 is a schematic comparison of two cars with different amounts of acceleration. In this regard, all kinds of diagrams can be classified as logical pictures. According to Niegemann et al. (2008; see also Leutner et al., 2014; Schnotz, 2002), diagrams such as pie charts, bar charts or line charts are more effective for learning than other forms of diagrams, because they are more familiar to learners. Furthermore, pie charts are especially suitable to convey information about the composition of a certain content to be learned and should be used when the learning content as a whole is of particular interest – for instance, when the distribution of the capacity of power generation for different sources in a country is demonstrated. When, on the other hand, quantitative differences between elements or information units need to be depicted, bar charts should be used (e.g., to show the development of alternative power generation over time).

Overall, when using logical pictures in multiple representations, one should make sure that learners are familiar with the conventions of how to process and interpret such representations (cf., Schnotz, 2002; Weidenmann, 1993). For instance, bar charts should show the bars in a bottom-up design and not from left to right.

To sum up, multiple external representations can be presented to learners in many different forms with each being more or less suitable to convey certain kinds or aspects of knowledge. In physics learning, all of such aspects (e.g., the retention of facts, the comprehension of mechanisms, the application and generalization of functional relations) have to be considered when an overall and complete range of conceptual and procedural knowledge and transfer are to be acquired. Besides the inherent characteristics of each representation, a second important factor that needs to be considered are individual learner characteristics, which can serve as moderators between instructional design and learning outcomes. These characteristics will be focused on in the next section.

The Role of Individual Learner Characteristics for Learning with Multiple Representations

The characteristics and individual prerequisites that learners bring into a certain learning scenario have been subject to a large amount of empirical studies, not only in physics and science teaching (e.g., Aufschnaiter, Duit, Fillbrandt & Niedderer, 1970; Duit, 2008; Incantalupo, Treagust & Koul, 2013), but also for learning with multiple representations in general. For instance, Mayer (2009) in his *individual differences principle* of the CTML states that multimedia design effects that are beneficial for low prior knowledge learners do not necessarily need to be as effective for high prior knowledge learners and can even be detrimental for them, for instance because of redundancy effects (Kalyuga & Sweller, 2014). In line with this, Kalyuga (2005) assumes an expertise reversal effect for instructional materials in that experts in a certain domain get along much better with reduced multimedia materials and less guidance. For instance, university students at later stages of their studies who are learning about the relativity theory might need remarkably less information than high school students who are just introduced to the theory.

A second learner prerequisite that appears to be especially important when it comes to learning with multiple representations that contain any kind of visual information is the spatial ability of a learner. For instance, according to Mayer and Moreno (1998), students with high spatial ability can better retain multiple visual representations in their working memory, relate such visual/spatial elements to each other and thus better learn when words are presented together with pictures. Spatial ability has been investigated especially with regard to dynamic representations (e.g., animations or videos), where Höffler (2010; Höffler & Leutner, 2011) found evidence for the so-called *ability-as-compensator* hypothesis. In other words, learners with low spatial ability might benefit more from dynamic visualizations because these provide an external representation of a process or procedure that helps learners to build an adequate mental model of the information to be learned, whereas constructing such a mental model by using static pictures should be much more difficult for low spatial ability learners (Hays, 1996).

Considering spatial ability as an important moderator between different multiple representations and learning success might be especially important in a domain that is as abstract as physics. On the one hand, much of the information found in instructional materials is pictorial (and thus very concrete); on the other hand different MERs require the construction of integrated mental models. We thus recommend taking spatial ability into account whenever research on physics learning includes (at least partly) visual multiple representations.

In addition to prior knowledge and spatial ability, several other learning characteristics have been focused on in recent research, including the cognitive style of learners, their epistemological beliefs, metacognitive and self-regulatory abilities and motivational as well as other affective variables. While these variables do not explicitly relate to learning with multiple representations, such variables can have an impact on how learners approach a learning situation, how they structure and regulate their learning process, or how much attention and perseverance they show during learning (cf., Duit, 1991; Höffler et al., 2014). Taken together, individual learner characteristics should be taken into account when designing instructional materials that contain multiple representations, as such characteristics can serve both as moderators (Schraw, Dunkle, & Bendixen, 1995) or mediators (Davis, Bagozzi, & Warshaw, 1989; Opfermann, 2008) between instructional design, strategies and activities deployed during learning as well as cognitive load and learning outcomes. Such characteristics determine how multiple representations are processed individually and whether learners are able to translate the external representation into an internal and coherent mental model (see also Gerjets & Hesse, 2004). This view is closely related to the *choreographies of teaching* view introduced by Oser and Baeriswyl (2001). This approach is shortly described in the last section of this chapter.

The Theory of Choreographies of Teaching

In the previous sections, we have described how multiple representations can be classified, which characteristics they should have and how they should be combined to support meaningful learning. In this discussion, we contextualize these representations by providing examples in physics and describe how individual learner characteristics relate to learning with multiple representations. In short, a certain instructional design that is effective for one learner might not be helpful for another and vice versa.

As a consequence, knowing as many external representations of a concept as possible and the logical connections between them is one of the necessary prerequisites to gain knowledge at university as well as at school and should therefore also be an important part of physics teachers' professional knowledge. This is in line with the "choreographies of teaching" introduced by Oser and Baeriswyl (2001; see also Geller, Neumann, & Fischer, 2014; Ohle, 2010). Their approach to learning emphasizes the need to design teaching explicitly according to learning goals. That is, not only the *sight structure* (everything that is visible, such as instructional materials including multiple external representations) of a lesson is important, but it has to be taken care of the *deep structure*, which comprises so called basis models and underlying processes of learning that should be supported. Teachers can introduce the deep structure of the discipline by providing learners with different instructional designs to choose from, which is also called *offers or opportunities to learn* in this approach. Similarly, Reyer (2004) distinguishes between the surface structure of a lesson and their deep structure, which includes learning processes, goals and strategies that can be applied by learners when a certain surface structure is provided.

For example, to understand the effect of gravity, learners need to *develop a prototype* in a first step. This might be supported by teachers showing the legendary apple of Newton paradigm in a demonstration – this would be a part of the sight or surface structure of the lesson. To build up a coherent mental model (as part of the deep structure), learners then need to interpret this visual external representation and to transfer the information into an internal text-based representation – an approach that is very similar to the ITPC approach by Schnotz (2005) and its description of building (text-based) propositional mental representations and (visual) mental models and integrating them into one coherent schema of the learning content. To organize their offers to learn and to support the students' construction of mental models, teachers should know several of such prototypes for the same concept. In a next step, the text-based prototype must be described in detail by *analyzing its essential categories and principles*, which includes the reconstruction of measurements and of mathematical modelling of underlying concepts. Third, to *deal actively with the concept* requires mental activities like the application of mathematical formalisms or of Newton's law of gravity or Newton's second law of motion, for instance by students conducting their own experiments. In this regard, a physics law is differently represented. In the first case it is used as the *description* of a phenomenon, and in the second case, it must be interpreted as a *source* to design an experiment. As a last step, learners should be able to *apply the developed concept in different situations*, like for example to describe the sun-earth-moon system or the gravity conditions in the International Space Station (ISS).

Following the model of Oser and Baeriswyl (2001), multiple external representations as part of the sight structure of a lesson should be used as a means to support processes related to the deep structure of the lesson.

Summary

In this introductory chapter, we have presented theories and approaches on learning with multiple external representations (MERs). We have argued that, based on well-established views on information processing and working memory, multiple external representations are suitable to foster learning, because in contrast to learning with single representations, MERs address different sensory and working memory channels instead of overloading only one channel. By using MERs, several functions that are beneficial for learning can be fulfilled – more specifically, they can support learning and deep level comprehension if they provide complementary information or address different cognitive processes and/or if they constrain each other's interpretation. We also emphasized that such beneficial effects do not only depend on the kind of representation combination (e.g. their spatial and temporal contiguity), but also on the inherent characteristics of the representations as well as on individual learner characteristics. Finally, the instructional design side and thus the sight structure of learning scenarios (e.g., MERs, their combination and characteristics) should be distinguished from the underlying deep structure, and multiple external representations as part of instructional materials should be designed according to this deep structure, for instance by offering learners different opportunities to learn using respectively related representations. This demand can be met by multiple external representations in a much better way than by single representations, because the inherent nature of MERs enables learners to choose between different representations and learn with the one that best fits their learning preferences, individual prerequisites or requirements and characteristics of the learning task.

To sum up, and as described above, using multiple external representations is a tool for facilitating the understanding of concepts for learners and for supporting them in task solving. In addition, using MERs is a necessary prerequisite for students' own construction and reconstruction of meaning not only from instructional materials provided but also to understand the internal structure of physics concepts expressed in different forms of representations. In turn, a broad knowledge of adequate external representations that can be used as such instructional materials is a necessary constituent of teachers' professional knowledge not only in physics education, but in general.

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