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Mechanistic reasoning in science education: A literature review

Rayendra Wahyu Bachtiar [1,2*], Ralph F. G. Meulenbroeks [1], Wouter R. van Joolingen [1]

[1] Freudenthal Institute, Utrecht University, Utrecht, THE NETHERLANDS
[2] Faculty of Teacher Training and Education, University of Jember, Jember, East Java, INDONESIA

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Abstract
There is a growing research interest in mechanistic reasoning (MR) in the field of science education, as this type of reasoning is perceived as an essential thinking skill for science education. This literature review synthesized 60 science education studies on MR published from 2006 to 2021. The findings showed three common aspects of conceptualizations of MR in science education: (1) causality in relation to MR, (2) use of entities and their associated activities, and (3) use of entities at (at least) one scale level below the scale level of a target phenomenon. While most of the reviewed studies related the importance of MR to cognitive aspects, a smaller number associated its value with scientific modelling. Three main difficulties in generating MR were categorized: (1) identifying and using unobservable entities, (2) assigning activities to entities, and (3) identifying and using an appropriate number of entities. Various types of support for fostering MR were identified. Implications and future studies are discussed.

Keywords: mechanistic reasoning, mechanistic explanations, science education, literature review

INTRODUCTION

One of the primary goals of science education is to invite students to act as scientists trying to provide scientific explanations of natural phenomena (NGSS Lead States, 2013; National Research Council, 2012). Scientific explanations can be based on different kinds of reasoning. For example, abductive reasoning refers to "an inferential process in the sense that it involves reasoning used to mentally derive causal claims (i.e., hypotheses/theories) from premises" (Lawson, 2010, p. 338). Hypothetical-deductive reasoning relies on generating plausible predictions (hypotheses) for an observed phenomenon, followed by an investigation to test the predictions (Ding, 2018). One form of causal reasoning which is often considered essential for science education is mechanistic reasoning (MR), the subject of our study (Krist et al., 2019; Robertson & Shaffer, 2016; Russ et al., 2008; Talanquer, 2018; van Mil et al., 2013).

MR requires reducing a phenomenon to the behavior of (in)visible entities that interact with each other (Russ et al., 2008; Talanquer, 2018). Consider the way two students, A and B, reason about the change in pressure of an ideal gas:

Student A: When the temperature rises, pressure increases.

Student B: When the temperature rises, the gas particles will have higher speeds; therefore, collisions between particles and the wall will become more forceful and frequent, resulting in an increase in pressure.

Both students link a cause to an effect. Whereas student A only mentions this link, student B's explanation additionally includes a mechanism underlying this causality. This mechanism illustrates how a change in temperature affects the pressure and is described in the form of entities (gas particles) and activities of those entities (collisions); in this case, the entities are not visible on the scale level of the phenomenon (i.e., the rise in pressure). Thus, student B's reasoning is called MR.

Studies in philosophy, e.g., Machamer et al. (2000), have contributed to establishing conceptualizations of MR. Other studies in science education have also tried to delineate the application of MR within domains such as physics (Robertson & Shaffer, 2016; Scherr & Robertson, 2015), biology (Haskel-Ittah et al., 2020a; van Mil et al.,

✉ r.w.bachtiar@uu.nl **(*Correspondence)** ✉ R.F.G.Meulenbroeks@uu.nl ✉ W.R.vanJoolingen@uu.nl

Contribution to the literature

- The literature study identified three essential aspects of mechanistic reasoning (MR): (1) causality, (2) use of entities and their associated activities, and (3) use of entities at (at least) one scale level below the scale level of a target phenomenon.
- Most of the reviewed studies relate the importance of MR in science education to cognitive aspects.
- In generating MR in science education, students face three main difficulties: identifying and using unobservable entities, assigning activities to entities, and identifying and using an appropriate number of entities.
- Examples of types of support for fostering MR in science education are given.

2016), and chemistry (Caspari et al., 2018a; Talanquer, 2018). As an important example, the oft-cited study by Russ et al. (2008) proposed elements of MR to identify how students think about an underlying mechanism of a physical phenomenon. Krist et al. (2019) synthesized existing frameworks for capturing MR, including Russ et al.'s (2008) study, to develop heuristics for MR emphasizing a requirement to think "at least one scalar [*sic*] level below the level of the target phenomenon" (Krist et al., 2019, p. 175). In the example above, the macroscopic phenomenon of a rise in pressure is explained in terms of the activities of unseen entities, i.e., the gas molecules. Some studies made use of an existing definition of MR to be applied to a particular domain. Dickes et al. (2016), for instance, drew on the work by Russ et al. (2008) to identify the development of students' conceptual understanding in the domain of ecology. Likewise, Moreira et al. (2019) also adapted Russ et al.'s (2008) framework to study students' conceptual understanding in a chemistry domain.

Many studies reported the value of MR in science education. For example, MR may be necessary for understanding complex phenomena, e.g., within molecular and cellular biology (Southard et al., 2016; van Mil et al., 2013). Also, a chemistry lesson focused on MR could support students' learning in chemistry (Crandell et al., 2019; Houchlei et al., 2021). As exemplified in studying organic chemistry reactions, MR is required to grasp the physical and chemical concepts behind existing formalisms (Caspari et al., 2018a, 2018b).

Despite its benefits in these situations, actually applying MR appears to remain challenging for students, however. Some studies have shown that students failed to exhibit MR because of a lack of domain-specific knowledge such as the molecular structure of a substance (Becker et al., 2016; Duncan & Reiser, 2007; Tate et al., 2020). Other studies have reported that when asked to explain a target phenomenon, students tended to provide descriptive accounts instead of MR, even after instruction on how to apply MR (Cooper et al., 2016; Talanquer, 2010). Efforts to promote students' MR include integrating MR into the curriculum (Crandell et al., 2019; Nawani et al., 2019) and the use of computer technology to elicit MR.

The considerable number of educational studies on MR in science, and the aforementioned issues call for a systematic synthesis. This study aims to review and synthesize the literature on MR in science education. The central questions for this literature review were:

1. What are the common aspects of conceptualizations of MR as proposed in the reviewed literature?
2. According to literature, why is MR considered to be important for science education?
3. According to literature, which difficulties do students encounter while generating MR?
4. According to literature, which strategies have been used to support students in generating MR?

The knowledge from this literature study is important not only for science education researchers, but also for science teachers who want to find ways to support students' MR. Possible uses of the findings are twofold. The first is to give an overview of the current state of the literature on MR for science education researchers. The second is to provide evidence-informed practical tips for science teachers.

METHOD

We followed the PRISMA approach (Moher et al., 2009) to report our procedure for searching, screening, and selecting relevant literature (see **Figure 1**).

Literature Search

The literature search started with searching for relevant articles in two databases: Scopus and Web of Science. We recognize that limiting the literature search to these databases might lead to a publication bias in the sample articles included in this review study. Nevertheless, we stuck to these two databases, because the scientific documents published in them have high quality and impact (Martín-Martín et al., 2018). In addition, articles published in our selected databases were mostly covered by other databases, such as Google Scholar. We employed the following keywords: [mechanistic AND reasoning OR mechanistic AND explanation*] AND [learning OR education OR student* OR learner*] AND [science OR physics OR biology OR chemistry] to search for articles published between 2006-

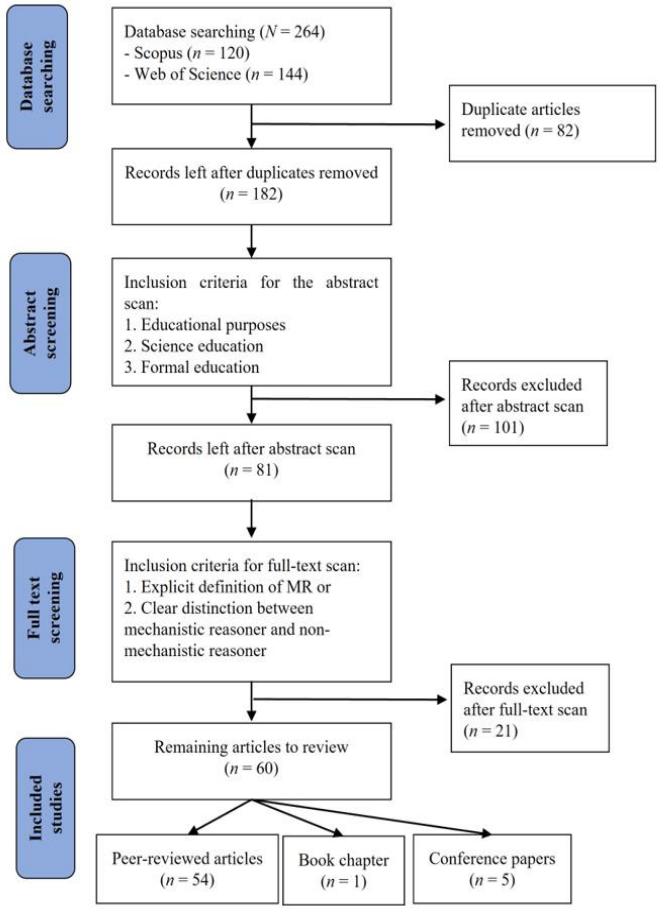

Figure 1. Literature search and selection process

2021 in these two databases. This limited timeframe was chosen because, as indicated by a preliminary search using a major search engine (i.e., Google Books Ngram Viewer), the number of publications containing 'mechanistic reasoning' sharply rose after 2006. Additionally, we applied a limitation search term [*Social science* OR *Psychology*] to our search in Scopus and [*Education* OR *Educational Research*] to our search in Web of Science. The search in these two databases resulted in a total of 264 articles.

Literature Selection

From the 264 search results, 92 duplicate articles were removed. The resulting 182 articles were screened in two steps. First, by scanning abstracts, articles were included in the synthesis when they addressed:

1. educational studies,
2. science education research (i.e., physics, biology, and/or chemistry), and
3. formal education.

In total, 101 articles that did not meet the criteria were excluded, leaving 81 articles.

The second screening included a full-text scan leading to the inclusion of articles that: either (1) explicitly provided conceptualizations of MR, or (2) made a clear distinction between students who exhibited

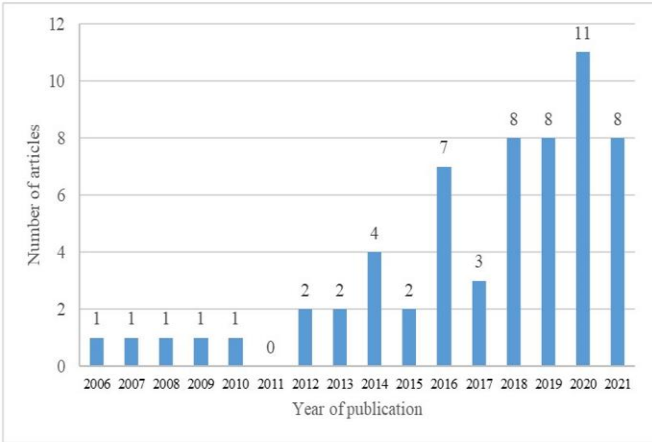

Figure 2. The distribution of the reviewed studies by year of publication

MR and those who did not. 21 articles were excluded because they did not meet at least one of these criteria, thus reducing the number of selected articles to 60. See **Figure 1** for an overview of the selection process.

Data Analysis

The sixty selected articles were reviewed in two steps. First, we extracted metadata information from the reviewed studies, such as publication year, domains (e.g., physics, biology, chemistry), and the educational level of research participants. Second, the full text of each article was scrutinized in order to identify the contribution of the reviewed studies to the four research questions. This was done in four steps:

1. articles that address a specific research question were selected by the lead author (note that one article may address more than one research question),
2. during ten, two-hour, plenary meetings with all authors present, the findings of the different studies were discussed at length, and divided into bottom-up categories related to the different research questions,
3. the lead author put the categories in writing, and
4. the resulting text was discussed with all authors, revised, and reviewed, until full agreement was reached.

The **Appendix A** lists all reviewed studies and their contribution to the answer to each research question.

RESULTS

Descriptive Overview of the Reviewed Studies

Figure 2 presents the distribution of the 60 reviewed studies by year of publication, between 2006 and 2021, and also illustrates the increase in science education research on MR.

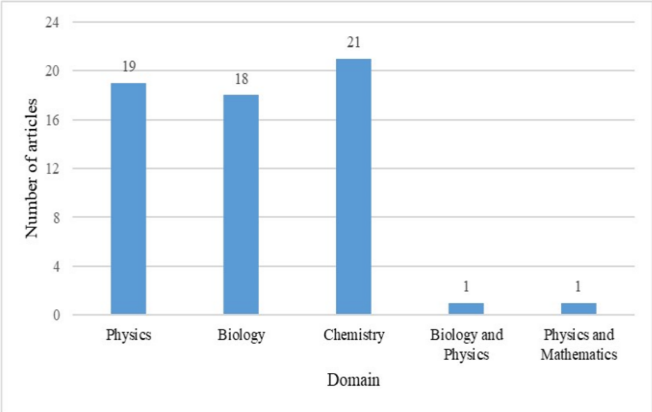

Figure 3. The distribution of the reviewed studies by domain(s)

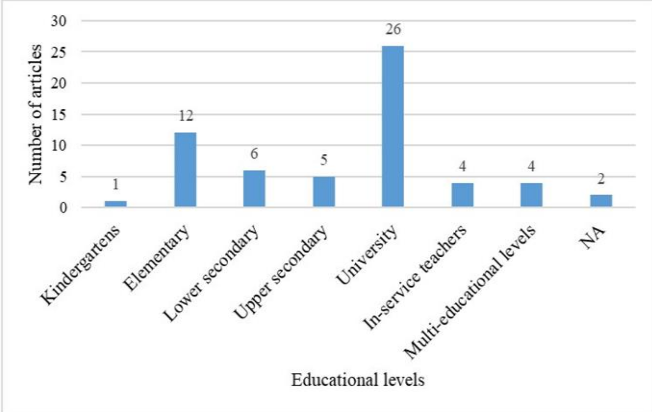

Figure 4. The distribution of the reviewed studies by the educational level of the research participants

There is almost the equal number of studies in the domains of physics, biology, and chemistry (see **Figure 3**). Among the 60 reviewed studies, two studies concern more than one domain, i.e., biology and physics (Krist et al., 2019) and physics and mathematics (Louca & Papademetri-Kachrimani, 2012). The educational level of research participants ranges from kindergarten to university (see **Figure 4**), and four out of 60 studies involved in-service teachers, e.g., Scherr and Robertson (2015). Two out of 60 studies, Moore (2021) and van Mil et al. (2013), do not explicitly refer to a specific grade level. The majority of the studies (26/60) involved university students. Four studies refer to multiple educational levels: Weinberg (2017a, 2017b, 2019) targeted elementary to university students, and Stevens et al. (2013) recruited both lower and upper secondary students.

The following sections present the findings, ordered by the corresponding research question.

RQ1: What Are the Common Aspects of Conceptualizations of MR as Proposed in the Reviewed Literature?

This section presents the findings relating to the first research question. Out of the 60 reviewed studies, 30 explicitly conceptualized MR, 13 referred to the conceptualization of MR provided by one or more of these 30 studies, and 17 studies did not provide conceptualizations of MR but only exemplified students who either exhibited MR or those who did not (see the appendix for the list of the 60 reviewed studies). Synthesizing the commonalities and differences in conceptualizations of MR provided by the 30 studies resulted in three common aspects of conceptualizations of MR:

1. causality in relation to MR,
2. basic elements of MR, and
3. the scale level of the basic elements of MR (see **Table 1** for the summary of these categories).

In dealing with the first aspect, i.e., causality in relation to MR, 30 studies refer to MR as a form of thinking about a mechanism representing an underlying process of a target phenomenon. As stated by Southard et al. (2016), MR requires thinking about "the interacting molecular mechanisms that underlie biological phenomena in the field of molecular biology" (Southard et al., 2016, p. 3). As exemplified, the molecular mechanism of translation presents a process illustrating ""binding" of the tRNA to the RNA transcript and ribosome and "recognition" of the ribosome binding site on the RNA by the ribosome" (Southard et al., 2016, p. 3). In addition to thinking about a mechanism, this mechanism not only presents a particular cause that leads to a particular effect but also depicts how this cause brings about the particular effect (Russ et al., 2008, 2009; Scherr & Robertson, 2015). Russ et al. (2009, p. 882) illustrate that MR about changes in pressure in an ideal gas entails describing a mechanism: i.e., "a smaller volume would mean more frequent collisions between gas particles and the wall of a container".

Among these 30 studies, three use the term *causal* MR to emphasize that explaining why and how a chemical reaction occurs requires involving both causal and mechanistic aspects (Cooper et al., 2016; Crandell et al., 2019, 2020). As exemplified in Cooper et al.'s (2016, p. 1705) study, exhibiting causal MR about acid-base reactions involves both the causes of reactions (causal aspect), i.e., "an electrostatic interaction between moieties of opposite (partial) charge", and the description of how the reactions occur (mechanistic aspect), i.e., "proton transfer or movement of electrons".

The second aspect relates to essential elements of MR. Twenty-six out of the 30 studies explicitly name two elements, i.e., entities and activities of entities, as the basic elements required to be included when generating MR. The basis for delineating these basic elements of MR goes back to the work by Machamer et al. (2000) and their colleagues i.e., Craver and Darden (2001) defining the concept of mechanisms, i.e.,

Table 1. The common aspects of MR as presented in the 30 studies (out of 60) providing an explicit conceptualization

Aspect	Findings	Studies
1. Causality in relation to MR	MR is a form of thinking about a mechanism that is inherently causal (N:30)	(Bachtiar et al., 2021; Becker et al., 2016; Bolger et al., 2012; Caspari et al., 2018a; Cooper et al., 2016; Crandell et al., 2019, 2020; de Andrade et al., 2021; Dickes et al., 2016; Haskel-Ittah et al., 2020a, 2020b; Haskel-Ittah & Yarden, 2018; Keiner & Graulich, 2020, 2021; Krist et al., 2019; Macrie-Shuck & Talanquer, 2020; Mathayas et al., 2021; Moore, 2021; Moreira et al., 2019; Russ et al., 2008, 2009; Scalco et al., 2018; Scherr & Robertson, 2015; Scott et al., 2018; Southard et al., 2016, 2017; Talanquer, 2018; Tang et al., 2020; van Mil et al., 2013; Watts et al., 2020)
2. Basic elements of MR	Entities and activities of these entities are explicitly mentioned as necessary elements of MR (N:26)	(Bachtiar et al., 2021; Caspari et al., 2018; Crandell et al., 2019, 2020; de Andrade et al., 2021; Dickes et al., 2016; Haskel-Ittah et al., 2020a, 2020b; Haskel-Ittah & Yarden, 2018; Keiner & Graulich, 2021, 2020; Krist et al., 2019; Macrie-Shuck & Talanquer, 2020; Mathayas et al., 2021; Moore, 2021; Moreira et al., 2019; Russ et al., 2008, 2009; Scalco et al., 2018; Scherr & Robertson, 2015; Southard et al., 2016, 2017; Talanquer, 2018; Tang et al., 2020; van Mil et al., 2013; Watts et al., 2020)
	Entities and activities of entities are implicitly considered as necessary elements of MR but are referred to under different, domain-specific, names (N:4)	(Becker et al., 2016; Bolger et al., 2012; Cooper et al., 2016; Scott et al., 2018)
3. Scale levels of the basic elements of MR	Studies describing the basic elements of MR, particularly referring to entities, at (at least) one scale level below the scale level of a target phenomenon	(Bachtiar et al., 2021; Becker et al., 2016; Bolger et al., 2012; Caspari et al., 2018a; Cooper et al., 2016; Crandell et al., 2019, 2020; de Andrade et al., 2021; Dickes et al., 2016; Haskel-Ittah et al., 2020a, 2020b; Haskel-Ittah & Yarden, 2018; Keiner & Graulich, 2020, 2021; Krist et al., 2019; Macrie-Shuck & Talanquer, 2020; Mathayas et al., 2021; Moore, 2021; Moreira et al., 2019; Russ et al., 2008, 2009; Scalco et al., 2018; Scherr & Robertson, 2015; Scott et al., 2018; Southard et al., 2016, 2017; Talanquer, 2018; Tang et al., 2020; van Mil et al., 2013; Watts et al., 2020)

> "Mechanisms are entities and activities organized such that they are productive of regular changes from start or set-up to finish or termination conditions. […] Mechanisms are composed of both entities (with their properties) and activities. Activities are the producers of change. Entities are the things that engage in activities" (p. 3).

For example, one oft-cited study by Russ et al. (2008) make use of Machamer et al.'s (2000) notion of mechanisms to propose a framework designed to identify students' MR. This framework consists of seven categories arranged in a hierarchy of the sophistication level of students' thinking about a mechanism:

1. describing the target phenomenon,
2. identifying setup conditions,
3. identifying entities,
4. identifying activities,
5. identifying properties of entities,
6. identifying organization of entities, and
7. chaining; see Russ et al. (2008) on page 512-513 for the full descriptions.

Chaining is considered as the most sophisticated form of MR. The study by Krist et al. (2019) relates their framework for MR, i.e., "identifying factors", "unpacking factors", and "linking", to the seven categories by Russ et al. (2008). Identifying factors encompasses three of seven categories, i.e., identifying entities, properties of entities and organization of entities, and "unpacking factors" and "linking" can be considered to respectively refer to "identifying activities" and "chaining" (Krist et al., 2019, p. 182-183). The studies in domains of biology (Haskel-Ittah et al., 2020b; Southard et al., 2016, 2017; van Mil et al., 2013) and chemistry (Keiner & Graulich, 2020, 2021; Macrie-Shuck & Talanquer, 2020; Moreira et al., 2019) introduce specific type of activities, i.e., interactions between entities. Likewise, Haskel-Ittah et al. (2020a) used the term 'function' to represent a specific type of activity in the genetic subject.

In four out of the 30 studies in the second aspect (i.e., Becker et al., 2016; Bolger et al., 2012; Cooper et al., 2016; Scott et al., 2018), elements of MR are referred to with domain-specific designations in which these elements implicitly refer to either entities or activities of these entities. As illustrated in Becker et al.'s (2016, p. 1714) study, MR about London dispersion forces entails describing two components, i.e., "causal factors" referring to electrons and "interactions among factors". These two components could be considered as entities (electrons) and activities of these entities (interactions) because these components are necessary to describe a mechanism underlying such chemical phenomena. Likewise, MR in an acid-base reaction requires to specify an underlying mechanism of reaction, i.e., "proton transfer or movement of electrons" (Cooper et al., 2016, p. 1705).

Table 2. The studies discussing the importance of MR

Category	n	Studies
1. Demonstrating deep conceptual understanding	15	(Balabanoff et al., 2020; Bolger et al., 2012; Caspari et al., 2018b; Cooper et al., 2016; Crandell et al., 2019; Geller et al., 2019; Haskel-Ittah & Yarden, 2018; Robertson & Shaffer, 2016; Scott et al., 2018; Southard et al., 2016; Talanquer, 2010; Tate et al., 2020; Weinberg, 2017b, 2019; Zotos et al., 2021)
2. Representing sophisticated explanations	10	(Becker et al., 2016; Dood et al., 2020; Haskel-Ittah et al., 2020a; Hsiao et al., 2019; Moreira et al., 2019; Richards et al., 2014; Schwarz et al., 2014; Sevian et al., 2018; Stevens et al., 2013; Weinrich & Talanquer, 2016)
3. Required to explain a molecular mechanism underlying a phenomenon.	9	(Caspari et al., 2018a, 2018b; Haskel-Ittah & Yarden, 2018; Houchlei et al., 2021; Krist et al., 2019; Moore, 2021; Newman et al., 2021; Scherr & Robertson, 2015; Southard et al., 2016)
4. Reflecting expert-like thinking	5	(Becker et al., 2016; Macrie-Shuck & Talanquer, 2020; Newman et al., 2021; Southard et al., 2016, 2017)
5. MR as a valuable assessment criterion	3	(Russ et al., 2008, 2009; Russ & Hutchison, 2006)
6. MR is considered as a valuable thinking strategy for meaningful engagement in scientific modelling	2	Schwarz et al., 2014; Wilkerson et al., 2018

Note. n: Number of studies

Also, Scott et al. (2018) reveals that MR about biological phenomena includes the description of "atomic-molecular interactions or cellular dynamics" (p. 3). In the context of simple mechanical systems, i.e., pegboard system of linkages, as revealed by Bolger et al. (2012), visible components of linkages (i.e., fixed pivot, floating pivot, and holder) represent entities and the contribution of these components to the system (e.g., the fixed pivot "constrains" motion in the system to be rotary (p. 178)) could be viewed as activities of entities. Additionally, Bolger et al. (2012) classify six types of students' MR about the simple mechanical systems:

1. related direction,
2. intermediary related direction,
3. rotation,
4. lever arms,
5. constraint via fixed pivot, and
6. constraint via holders.

The third aspect relates to a scale level of the basic elements of MR, particularly referring to entities. In all 30 reviewed studies giving an explicit conceptualization of MR, MR is considered to require the use of entities at (at least) one scale level below the scale level of a target phenomenon. Entities could be invisible, such as gas particles (e.g., Scherr & Robertson, 2015), or theoretical, such as energy, force, gravity (e.g., Krist et al., 2019; Russ et al., 2008). In addition to invisible entities, when a target phenomenon is microscopic in nature, e.g., chemical reactions, the associated entities refer to a submicroscopic level, such as electrons (e.g., Talanquer, 2018). In the context of MR in a particular phenomenon, such as ecology phenomena, or simple mechanical systems, all entities relevant to such phenomena are at visible levels (Bolger et al., 2012; Dickes et al., 2016; Krist et al., 2019), but they still refer to a part of a system. As exemplified by Krist et al. (2019), in ecological phenomena, e.g., changes in squirrel population, entities could be individual organisms, i.e., an individual squirrel or an individual seed.

Five out of the 30 studies explicitly argue that MR about complex phenomena, such as genetics, not only requires identification of invisible entities (e.g., molecules, atoms, or electrons), but also involves *multiple* entities (Haskel-Ittah et al., 2020b; Scalco et al., 2018; Southard et al., 2017; Talanquer, 2018; van Mil et al., 2013). Talanquer (2018) stated that MR about chemical phenomena needs to involve interactions of multiple particles at the submicroscopic level. MR about why oil does not dissolve in water entails consideration of the atomic composition and structure of each substance (analysis at the molecular scale) and the types of interactions among these particles (multiple entities).

RQ2: According to Literature, Why Is MR Considered to Be Important for Science Education?

Thirty-seven out of the 60 reviewed studies explicitly made statements on the importance of MR to science education. Based on these 37 studies, the importance of MR fell into six categories (**Table 2**). Note that one study may touch on more than one category.

Fifteen studies in category 1 showed that students who were capable of exhibiting MR demonstrated a deep conceptual understanding. For example, students' success in exhibiting MR reflected their ability to understand genetic phenomena (Brown et al., 2020; Haskel-Ittah et al., 2020b; Haskel-Ittah & Yarden, 2018; Tate et al., 2020), to make sense of photoelectric effects (Balabanoff et al., 2020), to comprehend the concepts behind organic chemistry reactions (Caspari et al., 2018a) and to draw correct mechanistic arrows for chemical reactions (Caspari et al., 2018b; Cooper et al., 2016; Crandell et al., 2019), to understand the motion in simple mechanical systems (Bolger et al., 2012; Weinberg, 2019), and to correctly predict the output motion in pegboard systems of linkages (Bolger et al., 2012).

Ten studies in category 2 reported that students using MR to explain a phenomenon were associated with the exhibition of more sophisticated explanations than those who did not use MR. For example, Becker et al. (2016) identified five levels of university students' reasoning about how and why the London dispersion forces occur. The students' explanations that reflected MR in this domain were categorized as the top level in sophistication.

Nine studies in category 3 stated that MR was needed to explain a molecular mechanism underlying a phenomenon. For example, MR was necessary to explain an underlying molecular mechanisms of biological phenomena (Southard et al., 2016), to explain and predict the outcome of chemical reactions (Houchlei et al., 2021), and to understand the process by which kinetic energy becomes thermal energy in an adiabatic process (Scherr & Robertson, 2015).

Specifically, among the studies assigned to category 1, 2, and 3, three pointed out the value of chaining (Hsiao et al., 2019; Scherr & Robertson, 2015; Weinberg, 2017b); according to Russ et al. (2008), chaining is considered as the highest level of MR. As exemplified in the study by Scherr and Robertson (2015), the use of chaining was necessary to explain the relationships between temperature and pressure through kinetic molecular theory; that is, how the change in volume of the gas influences the frequency of the gas particles-wall collisions. Likewise, Weinberg (2017b) found that the most difficult mechanistic elements of pegboard systems of linkages could be diagnosed by the students who used chaining. Hsiao et al. (2019) regarded chaining as another way to give a sophisticated explanation of a phenomenon.

Among the studies falling in category 1, 2 and 3, four showed that despite being able to exhibit MR, students' explanations were not guaranteed to be scientifically correct (Haskel-Ittah et al., 2020b; Krist et al., 2019; Robertson & Shaffer, 2016; Scherr & Robertson, 2015). Robertson and Shaffer (2016) studied university students' reasoning about the change in the pressure of an ideal gas. The students contended that a change in the pressure of an ideal gas was due to particle-particle collisions, not particle-wall collisions. The students thus exhibited MR about this phenomenon, but their explanations were not scientifically correct.

Another study, by Haskel-Ittah et al. (2020b), reported two types of mechanistic explanations generated by university students: namely direct interactions accounts and sensing-responding accounts; only the second type were relevant explanations of the particular genetic phenomenon, i.e., phenotypic plasticity.

Five studies grouped as category 4 illustrated that MR bears great similarities to the way in which actual scientists explain a phenomenon. In particular, two out of these four studies found that students' explanations of a phenomenon using chaining were aligned with expert-like thinking (Southard et al., 2016, 2017). In Southard et al.'s (2017) study, biologists and university students were interviewed and asked to explain a complex molecular-cellular phenomenon. The reasoning of seven students involved chaining, in which their explanations depicted mechanisms linking the genetic mutation and the cellular phenomenon of chemotaxis. Southard et al. (2017) noted that these students' reasoning aligned with that of the experts.

Three studies assigned to category 5 showed that MR was valuable when applied to an assessment criterion. For example, Russ and Hutchison (2006) demonstrated a student who provides incorrect explanations (but mechanistic) for the phenomenon of why a juice box caved in when sucking on the straw, that is (without considering the role of the air outside) "when the air that was pushing out on the box from the inside is removed, the box collapses" (p. 645).

Russ and Hutchison (2006) showed that if assessing the quality of students' inquiry was based on correctness, this student's inquiry was of no value at all because the student lacked understanding of air pressure. However, in terms of MR, the student's explanation can be attributed some merit, as the student's explanations involve an entity (air pressure) and an activity (pushing out), and even chaining as a high level of MR.

In two studies assigned to category 6, the use of MR as a way of thinking leads students to meaningful engagement in scientific modelling. In Wilkerson et al.'s (2018) study, for instance, fifth-grade students constructed a model of evaporation and condensation. The students who played what was called the EM&I game (focusing on entities, movement, and interactions) could provide better explanatory models of the phenomenon than those who did not play this game. These students in the EM&I game could create and use their model creation to mechanistically explain the phenomenon. That is, the students could use the models to invoke kinetic molecular theory when explaining the underlying molecular mechanisms of the phenomenon.

RQ3: According to Literature, What Difficulties Do Students Encounter While Generating MR?

Thirty out of the 60 reviewed studies specifically reported on students' difficulties in generating MR. We categorized the nature of their difficulties into three categories (see **Table 3**):

1. identifying and using unobservable entities,
2. assigning associated activities to entities, and
3. identifying and using an appropriate number of entities; note that one study may fall into more than one category.

Table 3. The studies addressing students' difficulties in generating MR

Categories of difficulties	n	Studies
1. Identifying and using unobservable entities	18	(Balabanoff et al., 2020; Becker et al., 2016; Cooper et al., 2016; Crandell et al., 2019; Dood et al., 2020; Haskel-Ittah et al., 2020a; Haskel-Ittah & Yarden, 2018; Moreira et al., 2019; Newman et al., 2021; Robertson & Shaffer, 2016; Scott et al., 2018; Southard et al., 2017; Speth et al., 2014; Talanquer, 2010, 2018; Tate et al., 2020; van Mil et al., 2016; Weinrich & Talanquer, 2016)
2. Assigning associated activities to entities	21	(Balabanoff et al., 2020; Becker et al., 2016; Bolger et al., 2012; Caspari et al., 2018a; Cooper et al., 2016; Crandell et al., 2019; Dood et al., 2020; Duncan & Reiser, 2007; Keiner & Graulich, 2020; Moreira et al., 2019; Nawani et al., 2019; Robertson & Shaffer, 2016; Scott et al., 2018; Sevian et al., 2018; Southard et al., 2016, 2017; Stevens et al., 2013; Watts et al., 2020; Weinrich & Talanquer, 2016; Wilkerson-Jerde et al., 2015; Zotos et al., 2021)
3. Identifying and using appropriate number of entities	5	(Scalco et al., 2018; Sevian et al., 2018; Southard et al., 2017; Talanquer, 2018; Weinrich & Talanquer, 2016)

Note. n: Number of studies

Identifying and using unobservable entities

As mentioned before, generating MR requires considering unobservable entities. Eighteen studies in category 1 reported students' failure to include entities at such a level. This failure was attributed to:

1. students' preference for superficial or "quick" explanations of a phenomenon and
2. actual lack of domain-specific knowledge.

With regard to the first issue, in 11 out of these 18 studies, when students were asked to explain a target phenomenon, they tended to just redescribe the phenomenon (Newman et al., 2021; Talanquer, 2010), to restate the configuration of chemical reactions (Cooper et al., 2016; Crandell et al., 2019; Dood et al., 2020; Weinrich & Talanquer, 2016), to reason at an observable scale (Balabanoff et al., 2020; Scott et al., 2018; Southard et al., 2017; Tang et al., 2020; Weinrich & Talanquer, 2016), or to rely on recognition or familiarity (Talanquer, 2018; Weinrich & Talanquer, 2016). It is noteworthy that the students in all of these studies had received a lesson on the subject, implying that, at least in principle, the relevant knowledge that could be used to invoke MR should have been available. For example, most of the undergraduate students in Scott et al.'s (2018) study focused on directly observable objects when asked to explain why an egg became solid when boiled. They focused on observable elements, for example, temperature change, and ignored unobservable entities responsible for the phenomenon.

With regard to the second issue, ten out of the 18 studies reported that students' lack of domain-specific knowledge led to an inability to identify relevant entities at unobservable levels. Among these 10 studies, three showed that students could not include relevant entities responsible for a target phenomenon because of their limited prior knowledge about the protein under consideration (van Mil et al., 2016), about the photoelectric effect (Balabanoff et al., 2020), and about freezing point depression (Moreira et al., 2019). For instance, when explaining cellular phenomena, such as a neutrophil chasing a bacterium, a 12th-grade student in van Mil et al.'s (2016) study could not identify molecular events underlying the phenomena. She argued that "The neutrophil 'smells' the bacterium […]" (van Mil et al. 2016, p. 552) and her explanations did not include any molecular dynamics. The researchers concluded that this omission occurred because the student did not have knowledge of appropriate entities at one scale below the cellular level.

Among ten studies in the second issue, three specifically investigated the way in which students' domain-specific knowledge contributes to students' ability to reason mechanistically (Haskel-Ittah et al., 2020a; Haskel-Ittah & Yarden, 2018; Robertson & Shaffer, 2016). Haskel-Ittah and Yarden (2018) investigated the extent to which 12th-grade students' conceptions of genes and traits involved the entity "protein" in explaining genetic phenomena.

The results showed that students holding causal conceptions (i.e., genes affect traits) did include proteins in their explanation, more so than their peers holding non-causal conceptions (i.e., genes *are* traits). Haskel-Ittah et al. (2020a) found that many seventh-grade students included proteins in their mechanistic explanations of a given genetic phenomenon but failed to transfer this to similar (but novel) phenomena. They suggested that students needed support in drawing on proteins as central entities in the mechanisms of genetic phenomena. In Robertson and Shaffer's (2016) study, many university students used the ideal gas law formula ($PV=nRT$) to simply state the linear relationship between temperature and pressure. The students did not involve unseen entities (e.g., gas particles) that is needed to explain the phenomenon mechanistically.

Assigning associated activities to entities

Students demonstrating MR not only recognize entities, but also assign appropriate activities to these entities. Twenty-one studies in category 2 reported students' failure to assign associated activities to entities. This failure was attributed to:

Table 4. The studies investigating types of support for MR (one study could be classified in one or more categories)

Type of support	n	Studies
1. Stimulating students to explain an underlying mechanism of a target phenomenon	12	(Bachtiar et al., 2021; Cooper et al., 2016; Crandell et al., 2020; de Andrade et al., 2021; Hsiao et al., 2019; Keiner & Graulich, 2021; Louca & Papademetri-Kachrimani, 2012; Richards et al., 2014; Tang et al., 2020; Weinrich & Talanquer, 2016; Wilkerson-Jerde et al., 2015; Wilkerson et al., 2018)
2. Heuristics guiding students to generate MR	2	(Krist et al., 2019; van Mil et al., 2013)
3. Facilitating students to construct mechanistic explanations	4	(Crandell et al., 2019; Dickes et al., 2016; Nawani et al., 2019; Suárez & Otero, 2014).
4. Using visual representations to help students understand an underlying mechanism of a target phenomenon	7	(Bolger et al., 2012; Brown et al., 2020; Mathayas et al., 2019, 2021; Scalco et al., 2018; Sevian et al., 2018; Tate et al., 2020)
5. Introducing students to relevant knowledge and supporting in using their knowledge to build MR	1	(van Mil et al., 2016)
6. Other factors influencing students' ability to invoke MR	3	(Weinberg, 2017a, 2017b; Weinrich & Talanquer, 2016)

Note. n: Number of studies

1. students considering entities as a cause of a target phenomenon but not specifying how these entities brought about the phenomenon,
2. students not having sufficient knowledge relating to the causes underlying a target phenomenon.

With regard to the former issue, 12 out of these 21 studies noted that students regarded entities as the cause of a target phenomenon but did not describe how these entities brought about the phenomenon. Even though the discussion of entities was included, students' explanations only conveyed a direct relation between entities and a target phenomenon. That is, entities cause an observed phenomenon to happen, without addressing *how* entities bring about the phenomenon, thus ignoring the activities of these entities. For example, Becker et al. (2016) found that when explaining how and why interactions between helium atoms arose, students referred to dipole formation in helium atoms as the cause of the electrical interactions. However, their explanations did not provide mechanisms leading to this formation. Even though the entity 'electron' was mentioned, the students did not explain how an electron behaved to result in a dipole formation, so their reasoning could not be labelled as MR. Likewise, some undergraduate students' explanations in Scott et al.'s (2018) study were categorized as what was called 'Emerging mechanistic frame' rather than MR, since the students recognize relevant molecules (entities) but are not describing the interactions among molecules (activities of entities). As an example, when a student attempted to explain why a blister forms after touching a hot pan, the student recognized two unseen entities, molecular change, and receptors in the skin. However, the student struggled to provide a mechanistic account of *how* heat brought about a molecular change in the first skin layer, thus forming the blister.

Turning to the latter, ten out of 21 studies noted that a lack of domain-specific knowledge relating to relevant entities contributed to students' inability to assign the relevant activities to entities. Southard et al. (2016), for instance, found that most of the university students in their study used inappropriate molecular entities when explaining DNA replication. Even though they were aware of the presence of these molecular entities, their attempt to make the connection between the presence of the entities and the phenomenon remained vague because they lacked an understanding of the molecular processes. Likewise, Duncan and Reiser (2007) revealed that a lack of understanding about proteins hindered students' ability to provide mechanistic explanations of genetic phenomena.

Identifying and using an appropriate number of entities

Explaining complex phenomena, such as genetic phenomena, in mechanistic ways requires considering the interactions of multiple entities. However, five studies in category 3 reported that students considered only a single entity (Scalco et al., 2018; Sevian et al., 2018; Southard et al., 2017; Talanquer, 2018; Weinrich & Talanquer, 2016). For example, Southard et al. (2017) found that many university students only considered a single entity when explaining biological phenomena. In another study, Scalco et al. (2018) reported that the university students in two different interventions considered only a single entity when generating explanations for the inability of water and carbon tetrachloride to mix, even though the interactions of multiple entities had been discussed during the lesson.

RQ4: According to Literature, What Strategies Have Been Used to Support Students in Generating MR?

This section presents the findings from 28 studies (out of 60) that reported on ways to support students in developing MR. We grouped them into six categories (see **Table 4**). The first five categories reflect a particular way of promoting students' MR; the sixth category is a catch-all for the remaining studies.

Stimulating students to think about an underlying mechanism of a target phenomenon

Twelve studies in category 1 presented types of support on stimulating students to explain an underlying mechanism of a target phenomenon, consequently exhibiting MR. In three out of 12 studies (Louca & Papademetri-Kachrimani, 2012; Richards et al., 2014; Tang et al., 2020), teacher support played a crucial role in prompting students to look at an underlying mechanism of a target phenomenon. Louca and Papademetri-Kachrimani (2012) found that kindergarten students were able to generate MR about a physical phenomenon, i.e., a floating-sinking object, after a teacher drew the students' attention to the different behaviors of two aluminum foil objects and asked them to explain how these different behaviors were caused. These researchers highlighted that to promote students' MR, teachers need to be able to foster students' spontaneous reasoning that has potential to gravitate towards MR and also be able to design activities to create opportunities for students to develop MR. Richards et al. (2014) gave two examples of a seventh-grade teacher's statements in the discussion of a free-fall motion phenomenon. When the teacher asked the students to identify the causal factors responsible for the movement of an object, the students only searched for the causes of this movement, for example, "maybe gravity" (p. 289). After the teacher asked the students to think about why and how the object moved the way it did (causal stories), the students succeeded in generating mechanistic explanations of the phenomenon.

Five out of 12 studies in category 1 showed that students were reasoning about an underlying mechanism of a target phenomenon when constructing a representation (Bachtiar et al., 2021; de Andrade et al., 2021; Hsiao et al., 2019; Wilkerson-Jerde et al., 2015; Wilkerson et al., 2018). For instance, Wilkerson-Jerde et al. (2015) investigated how fifth-grade students engaged in scientific modelling using multi-modelling tools, i.e., drawing, animation, and simulation, and used their model of smell diffusion to explain how an orange can be smelled from a certain distance. When working with drawing and animation, the students only focused on identifying entities representing what smell looked like, rather than depicting a process by which smell diffused. By using a simulation-based modelling tool, students started to think about mechanisms underlying smell diffusion; the model conveyed how the smell particles move and interact with each other so that these particles reach smellers at a certain distance.

Four out of 12 studies assigned to category 1 developed an explanation prompt designed to elicit students to provide a causal mechanism underlying chemical reactions (Cooper et al., 2016; Crandell et al., 2020; Keiner & Graulich, 2021; Weinrich & Talanquer, 2016). Cooper et al. (2016), for instance, investigated university students' reasoning about an acid-based reaction when provided with two types of questions: "[…] *what* you think is happening at the molecular level for this reaction" (type 1) and the same question with additional language, "using a molecular level explanation, please explain why this reaction occurs […]" (type 2) (p. 1706-1707). The findings showed that more university students were capable of providing mechanistic explanations when given type 2 questions rather than type 1. In the other studies, Weinrich and Talanquer (2016) noted that the nature of questions asked to university students may have led students to provide a mechanism underlying chemical reactions, but that further research on this effect was needed.

Heuristics guiding students to generating MR

Two studies in category 2 developed frameworks as heuristics designed to help students to think about a target phenomenon in mechanistic ways. Krist et al. (2019) proposed three essential heuristics applicable to guiding students' MR across science domains:

1. thinking across scalar levels,
2. identifying and unpacking relevant factors, and
3. linking.

Van Mil et al. (2013) developed a framework of so-called 'General structure of multi-level mechanistic explanations' dedicated to generating MR in molecular biology phenomena.

Facilitating students to construct mechanistic explanations

Four studies falling in category 3 designed a pedagogical approach facilitating students to construct mechanistic explanations of a target phenomenon (Brown et al., 2020; Crandell et al., 2019; Dickes et al., 2016; Nawani et al., 2019; Suárez & Otero, 2014). For instance, Crandell et al. (2019) conducted a longitudinal study on students' experience with a transformed chemistry curriculum (CLUE-GC) emphasizing why and how chemical phenomena occur as the basis for instruction. The findings showed that students from the CLUE-GC curriculum were more likely to be able to provide causal mechanistic explanations of simple acid-base reactions than those from other general chemistry courses.

Likewise, Nawani et al. (2019) used a form of inquiry-based learning (IBL) in molecular biology to investigate the effect on eleventh-grade students' conceptual understandings. The results showed that to begin with, many students had preconceptions that were based on their everyday experiences. However, the post-tests showed that conceptual understanding improved for some of these students, and they could provide mechanistic explanations of the biological phenomena, thus linking the use of IBL to the development of MR.

Using visual representations to help students understand an underlying mechanism of a target phenomenon

Seven studies in category 4 revealed that visual representations, namely, illustrated text and sequential images (Scalco et al., 2018), a simulation (Sevian et al., 2018), gesturing with a computer simulation (Mathayas et al., 2019, 2021), a technology-based explanation tool (Tate et al., 2020), a teacher-led classroom-based storybook intervention (Brown et al., 2020), and pegboard systems of linkages (Bolger et al., 2012), helped students to understand an underlying mechanism of a target phenomenon, and thereby, these representations provide some knowledge that students can use to exhibit MR. For example, Scalco et al. (2018) investigated the effect of two types of representation on the types of reasoning expressed by university students. These representations discussed and depicted the important relationships between molecular properties of matter (e.g., polarity) and the observed macroscopic behavior (e.g., immiscibility, the phenomenon that two liquids cannot mix). The first representation took the form of an illustrated text and an image, whereas the second only displayed sequential images without caption. The results showed that more students using the first representation could generate MR about the immiscibility of water and tetrachloride than those using the second representation.

Sevian et al. (2018) investigated the effect of two different instructional approaches on the complexity of university students' reasoning (where two out of four elements of complexity indicated MR ability) when learning kinetic molecular theory. One type of embodied learning instruction, whole-class kinesthetic activities, was used with group 1, in which the students acted as gas particles to model the behavior of gas particles when learning the effect of a change in volume on pressure. In group 2, the students learned kinetic molecular theory using a molecular dynamics simulation. By using this simulation, the students could simulate the gas particles' behavior by changing variables such as the number of particles, volume, temperature, and mass. The results found that students' ability to mechanistically explain why gaseous particles diffused improved more in group 2 than in group 1. Likewise, Mathayas et al. (2019) conducted a study on middle school students' use of hand gestures to interpret a visual model of the physical phenomena of heat transfer, air pressure, and the occurrence of seasons. The results showed that gesturing supported students in utilizing the model to articulate mechanistic explanations of the phenomena.

One study by Bolger et al. (2012) aimed to promote MR in children in Grades 2 and 5 in the context of a simple mechanical system. The components of the system were visible so that young students could easily identify the mechanisms by which elements interacted. The analysis of interview data showed that the students could exhibit MR about pegboard linkage systems; at least one element of the system was always mentioned.

Introducing students to relevant knowledge and supporting their use of knowledge to build MR

There was only one study (van Mil et al., 2016) devoted to introducing students to the specific knowledge required to invoke MR and providing support for use of the knowledge to exhibit MR. In developing their intervention, van Mil et al. (2016) revealed that to mechanistically explain biological phenomena, students need to connect molecular events with the phenomena at higher levels, such as cellular activities. To help students develop MR, the researchers designed an educational approach using molecular animations and graphics to introduce the basic knowledge of protein composition, structure, and chemistry; this knowledge is needed to make such connections. In this educational approach, a cognitive tool called a schematic representation of molecular MR was utilized in guiding students to use this knowledge to make the connection between the molecular and cellular levels. The results showed that many students' ability to provide mechanistic explanations of the phenomena improved.

Other factors influencing students' ability to use MR

Three studies reported that educational level (Weinrich & Talanquer, 2016), engineering experiences (Weinberg, 2017b), and mathematical knowledge (Weinberg, 2017a), contributed to students' ability to exhibit MR. For example, Weinrich and Talanquer (2016) showed that MR about chemical reactions was more prevalent among advanced undergraduate students than first-semester chemistry students.

DISCUSSION AND CONCLUSION

RQ1: What Are the Common Aspects of Conceptualizations of MR as Proposed in the Reviewed Literature?

Through synthesizing the commonalities and differences in conceptualizations of MR provided by 30 studies assigned to RQ1, the common aspects of MR were identified:

1. causality in relation to MR,
2. entities and their associated activities as the basic elements of MR, and
3. the use of entities at (at least) one scale level below the scale level of a target phenomenon.

As for causality, MR refers to a form of thinking about a mechanism that is *inherently* causal, meaning that a mechanism represents an underlying process of a target phenomenon. A mechanism does more than just illustrate which causes lead to a target phenomenon. It also depicts how causes bring about the phenomenon.

In relation to the basic elements of MR, in the studies using the terms originally delineated in Machamer et al.'s (2000) study, they all agree that generating MR requires including both elements, i.e., entities and activities of entities. Based on this common ground, we conclude that these two elements are the basic elements of MR. Thus, when describing an underlying mechanism of a target phenomenon, these basic elements require to be included.

Regarding the scale level of basic elements of MR, particularly concerning entities, MR involves the use of entities at (at least) one scale level below the scale level of a target phenomenon. These entities refer to invisible levels, e.g., water molecules, atoms, electrons, or theoretical entities, e.g., gravity, force, energy. Additionally, entities responsible for a particular phenomenon, such as ecology or simple mechanic systems, are concerned with visible levels. For example, an individual squirrel or seed was an entity involved in a mechanism for changes in a squirrel population (ecology phenomena) (Krist et al., 2019).

RQ 2: According to Literature, Why Is MR Considered to Be Important in Science Education?

The majority of the reviewed studies assigned to RQ2 associated the importance of MR with cognitive aspects. MR is considered as an important reasoning skill for science students. For example, students who were able to generate MR demonstrate a deep understanding of concepts, the use of MR resulted in sophisticated explanations of phenomena, and MR is necessary to explain a molecular mechanism underlying a phenomenon. MR can also serve as the basis for a valuable assessment criterion.

MR is also recommended as a valuable thinking strategy for scientific modelling (Wilkerson et al., 2018). When students use MR in this fashion, they construct and use a model to explain and predict unobservable mechanisms underlying a target phenomenon. Schwarz et al. (2009) refer to this as the highest level of scientific modelling practice. This implies that the use of MR as a thinking strategy may also have potential for students' engaging in authentic inquiry processes or model-based inquiry.

RQ 3: What Difficulties Do Students Face When Generating MR?

We found three main difficulties:

1. identifying and using unobservable entities,
2. using entities without addressing their associated activities, and
3. identifying and using an appropriate number of entities; the first two difficulties were more prevalent than the third one.

In addition, two reasons behind these difficulties were identified. First, even though students had already been introduced to some knowledge that could be used to generate plausible explanations, they appeared to prefer simple explanations, such as redescribing a target phenomenon, reasoning at observable scale levels, or considering entities as the cause of a target phenomenon but not specify how these entities brought about the phenomenon. Second, limited prior knowledge or prevailing misconceptions contribute to students' failure to use the basic elements of MR.

The findings indicate that generating MR is notoriously challenging for students. Constructing MR needs to consider both so-called domain-general reasoning, i.e., structural thinking about entities and activities, and domain-specific knowledge about relevant entities and appropriate activities being assigned to these entities. Generating MR does not preclude involving irrelevant entities and assigning incorrect activities to these entities, thus resulting in noncanonical mechanistic explanations, as shown in the studies by Krist et al. (2019) or Macrie-Shuck and Talanquer (2020). Thus, MR, especially in complex domains such as organic chemistry, or molecular biology, does require prior understanding of relevant concepts to identify appropriate entities and to assign associated activities to these entities (Newman et al., 2021).

RQ 4: According to Literature, What Strategies Have Been Used to Support Students in Generating MR?

Various types of support on MR were identified in the reviewed studies assigned to RQ4. Most of the studies provided support on stimulating students to explain a mechanism underlying a target phenomenon, thereby exhibiting MR. The support could be:

1. provided by teachers,
2. in the form of tasks-based explanations, and
3. through engaging students in constructing a model of a target phenomenon.

The other studies designed a pedagogical approach facilitating students to construct mechanistic explanations of a target phenomenon. A framework as heuristics was developed with the intent to guide students' MR. Some studies used visual representations, such as illustrated text and sequential images, to help students understand an underlying mechanism of a target phenomenon.

Among these reviewed studies, remarkably only one study, by van Mil et al. (2016), designed a pedagogical approach combining domain-specific knowledge and domain-general reasoning. The researchers introduced students to some basic knowledge required to understand a molecular mechanism underlying biological phenomena (domain-specific knowledge) and developed a framework as guidance on how to use the knowledge to generate MR about the phenomenon.

IMPLICATIONS, LIMITATIONS, AND FUTURE RESEARCH

This review study shows that MR is an important aspect of science education. Overall, its value is recognized for students' conceptual growth and ability to do modelling. However, promoting MR also requires some careful support to deal with challenges and to overcome the difficulties associated with it. Based on our findings, we suggest that developing support on MR should consider both domain-general reasoning (i.e., thinking about causal mechanisms in the form of entities and their associated activities at lower scale levels) and domain-specific knowledge (i.e., knowledge relevant to the entities and activities at these scale levels). Therefore, the support provided by science teachers should be twofold. First, on domain-general reasoning, teachers could stimulate students to think about causal mechanisms containing the elements of entities and their associated activities through, for instance, asking questions of why and how certain aspects of the observed phenomenon do arise. E.g., in electrostatics, how can small pieces of paper jump to a charged balloon? Second, teachers should make sure that students have the proper domain-specific knowledge necessary to actually work with the entities. In case of electrostatic phenomena, teachers need to furnish basic facts about matter, e.g., electrons and protons, and their properties, such as negative or positive charges. This could be accomplished by providing the students with an animation or fact sheet.

Although this review study presents overarching aspects of MR in science education, we recognize some limitations in the study. First, the search terms were limited to specific 'mechanistic reasoning' or 'mechanistic explanations' and did not include other terms that might relate to MR, such as causal mechanism or causal reasoning. Second, the selected studies focused on research on science education. We recognize that a long-standing study on MR in fields such as philosophy, psychology, or cognitive science, has contributed to the literature on MR. This research field might have a perspective on MR that has not yet been addressed in science education research, thus suggesting conducting future studies looking into either the common or different concepts of MR between science education studies and others.

This review also suggests some future research in order to gain more insight into MR in science education. First, this review study focuses on MR in science education research. We are also aware of other types of thinking skills that evoke causality, such as abductive reasoning. We suggest conducting a further theoretical study addressing the differences and overlap between MR and other types of thinking skills.

Second, only a small number of studies addressed the importance of MR as a thinking strategy used when engaging a learning process such as scientific modelling, compared to the value of MR for cognitive aspects. We see that the studies did not yet address what role MR plays in contributing to such scientific practices, or how it does so. Thus, it suggests the need for further studies exploring how MR leads students to engage in meaningful scientific modelling. In the context of scientific inquiry, there remains the need to do a further exploratory study on how MR supports students in conducting inquiry processes, such as formulating hypotheses. In addition, the value of MR linking to model-based inquiry (Windschitl et al., 2008) as a form of scientific practice combining inquiry and modelling, and a current issue on so-called 'sensemaking' (Odden & Russ, 2019, p. 187) as "the process of building explanations to resolve a perceived gap or conflict knowledge" could be a new research agenda on MR in science education.

Third, most studies that measured students' ability to exhibit MR concerning a specific phenomenon were conducted just after students had been introduced to the subject. Even so, some students' responses could not be characterized as MR. These findings raise questions as to why those students did not use their newly acquired knowledge to formulate MR. In the reviewed studies, we only found a few studies that may be used to address such questions (see Caspari et al., 2018b; Haskel-Ittah et al., 2020a; Haskel-Ittah & Yarden, 2018)). Thus, further research on not only measuring students' MR, but also understanding how domain-specific knowledge contributes to MR (for different science domains) is needed. Gaining a clear answer to such questions may contribute to the better design of instructional strategies supporting students' MR.

Fourth, in this review study, regarding types of support, only one article in category 5 was found, that is, providing the necessary domain-specific knowledge and supporting students in using this knowledge to generate MR (see **Table 4**), in the field of biology. We contend that this type of support is important because different science domains have their own characteristics. This was emphasized in a recent study by Schwarz et al. (2020), which revealed that what counts as mechanisms in one domain may not do so in other domains, so that each domain might require a particular way to support students' MR. Thus, more studies are needed on the effectiveness of instructional strategies for promoting MR in a specific domain.

Fifth, Russ et al. (2008) introduced chaining as the highest level of MR, and some studies supported it and showed its value. However, few studies explored the contribution of chaining in science learning more closely; see Caspari et al. (2018b) as an example. Thus, exploring students' success in achieving chaining and strategies for promoting their use of chaining might be a promising pathway for future research on MR in science education.

Overall, the current review study has shown the potential of MR in science education, providing insights into both the theoretical and practical aspects needed for students' successful introduction to the more advanced aspects of science.

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REFERENCES

Bachtiar, R. W., Meulenbroeks, R. F. G., & van Joolingen, W. R. (2021). Stimulating mechanistic reasoning in physics using student-constructed stop-motion animations. *Journal of Science Education and Technology, 30*(6), 777-790. https://doi.org/10.1007/s10956-021-09918-z

Balabanoff, M. E., Al Fulaiti, H., Bhusal, S., Harrold, A., & Moon, A. C. (2020). An exploration of chemistry students' conceptions of light and light-matter interactions in the context of the photoelectric effect. *International Journal of Science Education, 42*(6), 861-881. https://doi.org/10.1080/09500693.2020.1736358

Becker, N., Noyes, K., & Cooper, M. (2016). Characterizing students' mechanistic reasoning about London dispersion forces. *Journal of Chemical Education, 93*(10), 1713-1724. https://doi.org/10.1021/acs.jchemed.6b00298

Bolger, M. S., Kobiela, M., Weinberg, P. J., & Lehrer, R. (2012). Children's mechanistic reasoning. *Cognition and Instruction, 30*(2), 170-206. https://doi.org/10.1080/07370008.2012.661815

Brown, S. A., Ronfard, S., & Kelemen, D. (2020). Teaching natural selection in early elementary classrooms: Can a storybook intervention reduce teleological misunderstandings? *Evolution: Education and Outreach, 13*, 12. https://doi.org/10.1186/s12052-020-00127-7

Caspari, I., Kranz, D., & Graulich, N. (2018a). Resolving the complexity of organic chemistry students' reasoning through the lens of a mechanistic framework. *Chemistry Education Research and Practice, 19*(4), 1117-1141. https://doi.org/10.1039/c8rp00131f

Caspari, I., Weinrich, M. L., Sevian, H., & Graulich, N. (2018b). This mechanistic step is "productive": Organic chemistry students' backward-oriented reasoning. *Chemistry Education Research and Practice, 19*(1), 42-59. https://doi.org/10.1039/c7rp00124j

Cooper, M. M., Kouyoumdjian, H., & Underwood, S. M. (2016). Investigating students' reasoning about acid-base reactions. *Journal of Chemical Education, 93*(10), 1703-1712. https://doi.org/10.1021/acs.jchemed.6b00417

Crandell, O. M., Kouyoumdjian, H., Underwood, S. M., & Cooper, M. M. (2019). Reasoning about reactions in organic chemistry: Starting it in general chemistry. *Journal of Chemical Education, 96*(2), 213-226. https://doi.org/10.1021/acs.jchemed.8b00784

Crandell, O. M., Lockhart, M. A., & Cooper, M. M. (2020). Arrows on the page are not a good gauge: Evidence for the importance of causal mechanistic explanations about nucleophilic substitution in organic chemistry. *Journal of Chemical Education, 97*(2), 313-327. https://doi.org/10.1021/acs.jchemed.9b00815

Craver, C. F., & Darden, L. (2001). Discovering mechanisms in neurobiology: The case of spatial memory. In P. K. Machamer, R. Grush, & P. McLaughlin (Eds.), *Theory and method in the neurosciences* (pp. 112-137). University of Pittsburgh Press.

de Andrade, V., Shwartz, Y., Freire, S., & Baptista, M. (2021). Students' mechanistic reasoning in practice: Enabling functions of drawing, gestures, and talk. *Science Education, 106*(1), 199-225. https://doi.org/10.1002/sce.21685

Dickes, A. C., Sengupta, P., Farris, A. V., & Basu, S. (2016). Development of mechanistic reasoning and multilevel explanations of ecology in third grade using agent-based models. *Science Education, 100*(4), 734-776. https://doi.org/10.1002/sce.21217

Ding, L. (2018). Progression trend of scientific reasoning from elementary school to university: A large-scale cross-grade survey among Chinese students. *International Journal of Science and Mathematics Education, 16*(8), 1479-1498. https://doi-org/10.1007/s10763-017-9844-0

Dood, A. J., Dood, J. C., Cruz-Ramírez De Arellano, D., Fields, K. B., & Raker, J. R. (2020). Analyzing explanations of substitution reactions using lexical analysis and logistic regression techniques. *Chemistry Education Research and Practice, 21*(1), 267-286. https://doi.org/10.1039/c9rp00148d

Duncan, R. G., & Reiser, B. J. (2007). Reasoning across ontologically distinct levels: Students' understandings of molecular genetics. *Journal of Research in Science Teaching, 44*(7), 938-959. https://doi.org/10.1002/tea.20186

Geller, B. D., Gouvea, J., Dreyfus, B. W., Sawtelle, V., Turpen, C., & Redish, E. F. (2019). Bridging the gaps: How students seek disciplinary coherence in introductory physics for life science. *Physical Review Physics Education Research, 15*(2), 020142. https://doi.org/10.1103/PhysRevPhysEducRes.15.020142

Haskel-Ittah, M., Duncan, R. G., Vázquez-Ben, L., & Yarden, A. (2020a). Reasoning about genetic mechanisms: Affordances and constraints for learning. *Journal of Research in Science Teaching, 57*(3), 342-367. https://doi.org/10.1002/tea.21595

Haskel-Ittah, M., Duncan, R. G., & Yarden, A. (2020b). Students' understanding of the dynamic nature of genetics: Characterizing undergraduates' explanations for interaction between genetics and environment. *CBE – Life Sciences Education, 19*(3), 1-13. https://doi.org/10.1187/cbe.19-11-0221

Haskel-Ittah, M., & Yarden, A. (2018). Students' conception of genetic phenomena and its effect on their ability to understand the underlying mechanism. *CBE – Life Sciences Education, 17*(3), ar36. https://doi.org/10.1187/cbe.18-01-0014

Houchlei, S. K., Bloch, R. R., & Cooper, M. M. (2021). Mechanisms, models, and explanations: Analyzing the mechanistic paths students take to reach a product for familiar and unfamiliar organic reactions. *Journal of Chemical Education, 98*(9), 2751-2764. https://doi.org/10.1021/acs.jchemed.1c00099

Hsiao, L., Lee, I., & Klopfer, E. (2019). Making sense of models: How teachers use agent-based modeling to advance mechanistic reasoning. *British Journal of Educational Technology, 50*(5), 2203-2216. https://doi.org/10.1111/bjet.12844

Keiner, L., & Graulich, N. (2020). Transitions between representational levels: Characterization of organic chemistry students' mechanistic features when reasoning about laboratory work-up procedures. *Chemistry Education Research and Practice, 21*(1), 469-482. https://doi.org/10.1039/c9rp00241c

Keiner, L., & Graulich, N. (2021). Beyond the beaker: Students' use of a scaffold to connect observations with the particle level in the organic chemistry laboratory. *Chemistry Education Research and Practice, 22*(1), 146-163. https://doi.org/10.1039/d0rp00206b

Krist, C., Schwarz, C. V., & Reiser, B. J. (2019). Identifying essential epistemic heuristics for guiding mechanistic reasoning in science learning. *Journal of the Learning Sciences, 28*(2), 160-205. https://doi.org/10.1080/10508406.2018.1510404

Lawson, A. E. (2010). Basic inferences of scientific reasoning, argumentation, and discovery. *Science Education, 94*(2), 336-364.

Louca, T. L., & Papademetri-Kachrimani, C. (2012). Asking for too much too early? Promoting mechanistic reasoning in early childhood science and mathematics education. In J. van Aalst, K. Thompson, M. J. Jacobson, & P. Reimann (Eds.), *Proceedings of the 10th International Conference of the Learning Sciences: The Future of Learning* (pp. 513-514). International Society of the Learning Sciences.

Machamer, P., Darden, L., & Craver, C. F. (2000). Thinking about mechanisms. *Philosophy of Science, 67*(1), 1-25. https://doi.org/10.1086/392759

Macrie-Shuck, M., & Talanquer, V. (2020). Exploring students' explanations of energy transfer and transformation. *Journal of Chemical Education, 97*(12), 4225-4234. https://doi.org/10.1021/acs.jchemed.0c00984

Martín-Martín, A., Orduna-Malea, E., Thelwall, M., & López-Cózar, E. D. (2018). Google Scholar, Web of Science, and Scopus: A systematic comparison of citations in 252 subject categories. *Journal of Informetrics, 12*(4), 1160-1177. https://doi.org/10.1016/j.joi.2018.09.002

Mathayas, N., Brown, D. E., & Lindgren, R. (2021). "I got to see, and I got to be a part of it": How cued gesturing facilitates middle-school students' explanatory modeling of thermal conduction. *Journal of Research in Science Teaching, 58*(10), 1557-1589. https://doi.org/10.1002/tea.21718

Mathayas, N., Brown, D. E., Wallon, R. C., & Lindgren, R. (2019). Representational gesturing as an epistemic tool for the development of mechanistic explanatory models. *Science Education, 103*(4), 1047-1079. https://doi.org/10.1002/sce.21516

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Journal of Clinical Epidemiology, 62*(10), 1006-1012. https://doi.org/10.1016/j.jclinepi.2009.06.005

Moore, C. (2021). Designing a curriculum for the networked knowledge facet of systems thinking in secondary biology courses: A pragmatic framework. *Journal of Biological Education*. https://doi.org/10.1080/00219266.2021.1909641

Moreira, P., Marzabal, A., & Talanquer, V. (2019). Using a mechanistic framework to characterize chemistry students' reasoning in written explanations. *Chemistry Education Research and Practice, 20*(1), 120-131. https://doi.org/10.1039/c8rp00159f

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.

Nawani, J., von Kotzebue, L., Spangler, M., & Neuhaus, B. J. (2019). Engaging students in constructing scientific explanations in biology classrooms: A lesson-design model. *Journal of Biological Education, 53*(4), 378-389. https://doi.org/10.1080/00219266.2018.1472131

Newman, D. L., Coakley, A., Link, A., Mills, K., & Wright, L. K. (2021). Punnett squares or protein production? The expert–novice divide for conceptions of genes and gene expression. *CBE Life Sciences Education, 20*(4), 1-10. https://doi.org/10.1187/CBE.21-01-0004

NGSS Lead States. (2013). Next generation science standards: For states, by states. *National Academies Press*. http://www.nextgenscience.org/get-to-know

Odden, T. O. B., & Russ, R. S. (2019). Defining sensemaking: Bringing clarity to a fragmented theoretical construct. *Science Education, 103*(1), 187-205. https://doi.org/10.1002/sce.21452

Richards, J., Elby, A., & Gupta, A. (2014). Characterizing a new dimension of change in attending and responding to the substance of student thinking. In J. L. Polman, E. A. Kyza, D. K. O'Neill, I. Tabak, W. R. Penuel, A. S. Jurow, K. O'Connor, T. Lee, & L. D'Amico (Eds.), *Proceedings of the 11th International Conference of the Learning Sciences: Learning and Becoming in Practice* (pp. 286-293). International Society of the Learning Sciences.

Robertson, A. D., & Shaffer, P. S. (2016). University student reasoning about the basic tenets of kinetic-molecular theory, Part II: Pressure of an ideal gas. *American Journal of Physics, 84*(10), 795-809. https://doi.org/10.1119/1.4960215

Russ, R. S., Coffey, J. E., Hammer, D., & Hutchison, P. (2009). Making classroom assessment more accountable to scientific reasoning: A case for attending to mechanistic thinking. *Science Education, 93*(5), 875-891. https://doi.org/10.1002/sce.20320

Russ, R. S., & Hutchison, P. (2006). It's okay to be wrong: Recognizing mechanistic reasoning during student inquiry. In S. A. Barab, K. E. Hay, & D. T. Hickey (Eds.), *Proceedings of the 7th International Conference of the Learning Sciences* (pp. 641-647). International Society of the Learning Sciences.

Russ, R. S., Scherr, R. E., Hammer, D., & Mikeska, J. (2008). Recognizing mechanistic reasoning in student scientific inquiry: A framework for discourse analysis developed from philosophy of science. *Science Education, 92*(3), 499-525. https://doi.org/10.1002/sce.20264

Scalco, K. C., Talanquer, V., Kiill, K. B., & Cordeiro, M. R. (2018). Making sense of phenomena from sequential images versus illustrated text. *Journal of Chemical Education, 95*(3), 347-354. https://doi.org/10.1021/acs.jchemed.7b00716

Scherr, R. E., & Robertson, A. D. (2015). Productivity of "collisions generate heat" for reconciling an energy model with mechanistic reasoning: A case study. *Physical Review Special Topics-Physics Education Research, 11*(1), 010111. https://doi.org/10.1103/PhysRevSTPER.11.010111

Schwarz, C., Cooper, M., Long, T., Trujillo, C., Noyes, K., de Lima, J., Kesh, J., & Stolzfus, J. (2020). Mechanistic explanations across undergraduate chemistry and biology courses. In M. Gresalfi, & I. S. Horn (Eds.), *Proceedings of the 14th International Conference of the Learning Sciences: Interdisciplinarity of the Learning Sciences* (pp. 625-628). International Society of the Learning Sciences.

Schwarz, C. V., Ke, L., Lee, M., & Rosenberg, J. (2014). Developing mechanistic model-based explanations of phenomena: Case studies of two fifth grade students' epistemologies in practice over time. In J. L. Polman, E. A. Kyza, D. K. O'Neill, I. Tabak, W. R. Penuel, A. S. Jurow, K. O'Connor, T. Lee, & L. D'Amico (Eds.), *Proceedings of the 11th International Conference of the Learning Sciences: Learning and Becoming in Practice* (pp. 182-189). International Society of the Learning Sciences.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632-654. https://doi.org/10.1002/tea.20311

Scott, E. E., Anderson, C. W., Mashood, K. K., Matz, R. L., Underwood, S. M., & Sawtelle, V. (2018). Developing an analytical framework to characterize student reasoning about complex processes. *CBE – Life Sciences Education, 17*(3), ar49. https://doi.org/10.1187/cbe.17-10-0225

Sevian, H., Hugi-Cleary, D., Ngai, C., Wanjiku, F., & Baldoria, J. M. (2018). Comparison of learning in two context-based university chemistry classes. *International Journal of Science Education, 40*(10), 1239-1262. https://doi.org/10.1080/09500693.2018.1470353

Southard, K., Espindola, M. R., Zaepfel, S. D., & Bolger, M. S. (2017). Generative mechanistic explanation building in undergraduate molecular and cellular biology. *International Journal of Science Education, 39*(13), 1795-1829. https://doi.org/10.1080/09500693.2017.1353713

Southard, K., Wince, T., Meddleton, S., & Bolger, M. S. (2016). Features of knowledge building in biology: Understanding undergraduate students' ideas about molecular mechanisms. *CBE – Life Sciences Education, 15*(1), ar7. https://doi.org/10.1187/cbe.15-05-0114

Speth, E. B., Shaw, N., Momsen, J., Reinagel, A., Le, P., Taqieddin, R., & Long, T. (2014). Introductory biology students' conceptual models and explanations of the origin of variation. *CBE – Life*

Sciences Education, 13(3), 529-539. https://doi.org/10.1187/cbe.14-02-0020

Stevens, S. Y., Shin, N., & Peek-Brown, D. (2013). Learning progressions as a guide for developing meaningful science learning: A new framework for old ideas. *Educación Química* [*Chemical Education*], *24*(4), 381-390. https://doi.org/10.1016/S0187-893X(13)72491-1

Suárez, E., & Otero, V. (2014). Leveraging the cultural practices of science for making classroom discourse accessible to emerging bilingual students. In J. L. Polman, E. A. Kyza, D. K. O'Neill, I. Tabak, W. R. Penuel, A. S. Jurow, K. O'Connor, T. Lee, & L. D'Amico (Eds.), *Proceedings of the 11th International Conference of the Learning Sciences: Learning and Becoming in Practice* (pp. 800-807). International Society of the Learning Sciences.

Talanquer, V. (2010). Exploring dominant types of explanations built by general chemistry students. *International Journal of Science Education, 32*(18), 2393-2412. https://doi.org/10.1080/09500690903369662

Talanquer, V. (2018). Exploring mechanistic reasoning in chemistry. In J. Yeo, T. W. Teo, & K.-S. Tang (Eds.), *Science education research and practice in Asia-Pacific and beyond* (pp. 39-52). Springer. https://doi.org/10.1007/978-981-10-5149-4_3

Tang, X., Elby, A., & Hammer, D. (2020). The tension between pattern-seeking and mechanistic reasoning in explanation construction: A case from Chinese elementary science classroom. *Science Education, 104*(6), 1071-1099. https://doi.org/10.1002/sce.21594

Tate, E. D., Ibourk, A., McElhaney, K. W., & Feng, M. (2020). Middle school students' mechanistic explanation about trait expression in rice plants during a technology-enhanced science inquiry investigation. *Journal of Science Education and Technology, 29*(5), 677-690. https://doi.org/10.1007/s10956-020-09846-4

van Mil, M. H. W., Boerwinkel, D. J., & Waarlo, A. J. (2013). Modelling molecular mechanisms: A framework of scientific reasoning to construct molecular-level explanations for cellular behavior. *Science & Education, 22*(1), 93-118. https://doi.org/10.1007/s11191-011-9379-7

van Mil, M. H. W., Postma, P. A., Boerwinkel, D. J., Klaassen, K., & Waarlo, A. J. (2016). Molecular mechanistic reasoning: Toward bridging the gap between the molecular and cellular levels in life science education. *Science Education, 100*(3), 517-585. https://doi.org/10.1002/sce.21215

Watts, F. M., Schmidt-McCormack, J. A., Wilhelm, C. A., Karlin, A., Sattar, A., Thompson, B. C., Gere, A. R., & Shultz, G. V. (2020). What students write about when students write about mechanisms: Analysis of features present in students' written descriptions of an organic reaction mechanism. *Chemistry Education Research and Practice, 21*(4), 1148-1172. https://doi.org/10.1039/c9rp00185a

Weinberg, P. J. (2017a). Mathematical description and mechanistic reasoning: A pathway toward STEM integration. *Journal of Pre-College Engineering Education Research, 7*(1), 90-107. https://doi.org/10.7771/2157-9288.1124

Weinberg, P. J. (2017b). Supporting mechanistic reasoning in domain-specific contexts. *Journal of Pre-College Engineering Education Research, 7*(2), 27-39. https://doi.org/10.7771/2157-9288.1127

Weinberg, P. J. (2019). Assessing mechanistic reasoning: Supporting systems tracing. *Journal of Pre-College Engineering Education Research, 9*(1), 30-54. https://doi.org/10.7771/2157-9288.1182

Weinrich, M. L., & Talanquer, V. (2016). Mapping students' modes of reasoning when thinking about chemical reactions used to make a desired product. *Chemistry Education Research and Practice, 17*(2), 394-406. https://doi.org/10.1039/c5rp00208g

Wilkerson, M. H., Shareff, R., Laina, V., & Gravel, B. (2018). Epistemic gameplay and discovery in computational model-based inquiry activities. *Instructional Science, 46*(1), 35-60. https://doi.org/10.1007/s11251-017-9430-4

Wilkerson-Jerde, M. H., Gravel, B. E., & Macrander, C. A. (2015). Exploring shifts in middle school learners' modeling activity while generating drawings, animations, and computational simulations of molecular diffusion. *Journal of Science Education and Technology, 24*(2-3), 396-415. https://doi.org/10.1007/s10956-014-9497-5

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education, 92*(5), 941-967. https://doi.org/10.1002/sce.20259

Zotos, E. K., Tyo, J. J., & Shultz, G. V. (2021). University instructors' knowledge for teaching organic chemistry mechanisms. *Chemistry Education Research and Practice, 22*(3), 715-732. https://doi.org/10.1039/d0rp00300j

APPENDIX A

An Overview of the Selected Articles

Table A1. An overview of the selected articles

No	Author(s)	Year	Educational level[1]	Domain	RQ1[2]	RQ2[3]	RQ3[3]	RQ4[3]
1	Bachtiar, Meulenbroeks & van Joolingen	2021	Lower secondary	Physics	Conceptualizations			√
2	Balabanoff, Al Fulaiti, Bhusal, Harrold, & Moon	2020	University	Physics	Student	√	√	
3	Becker, Noyes, & Cooper	2016	University	Chemistry	Conceptualizations	√	√	
4	Bolger, Kobiela, Weinberg, & Lehrer	2012	Elementary	Physics	Conceptualizations	√	√	√
5	Brown, Ronfard, & Kelemen	2020	Elementary	Biology	Student			√
6	Caspari, Kranz, & Graulich	2018	University	Chemistry	Conceptualizations	√	√	
7	Caspari, Weinrich, Sevian, & Graulich	2018	University	Chemistry	Adoption	√		
8	Cooper, Kouyoumdjian, Underwood, Kouyourndjian, & Underwood	2016	University	Chemistry	Conceptualizations	√	√	√
9	Crandell, Kouyoumdjian, Underwood, & Cooper	2019	University	Chemistry	Conceptualizations	√	√	√
10	Crandell, Lockhart, & Cooper	2020	University	Chemistry	Conceptualizations			√
11	de Andrade, Shwartz, Freire, & Baptista	2021	Lower secondary	Chemistry	Conceptualizations			√
12	Dickes, Sengupta, Farris, & Basu	2016	Elementary	Biology	Conceptualizations			√
13	Dood, A J., Dood, J C., de Arellano, Fields, & Raker	2020	University	Chemistry	Adoption	√	√	
14	Duncan & Reiser	2007	Upper secondary	Biology	Student		√	
15	Geller, Gouvea, Dreyfus, Sawtelle, Turpen, & Redish	2019	University	Physics	Student	√		
16	Haskel-Ittah & Yarden	2018	Upper secondary	Biology	Conceptualizations	√	√	
17	Haskel-Ittah, Duncan, Vázquez-Ben, & Yarden	2020	Lower secondary	Biology	Conceptualizations		√	
18	Haskel-Ittah, Duncan, & Yarden	2020	University	Biology	Conceptualizations	√		
19	Houchlei, Bloch, & Cooper	2021	University	Chemistry	Student	√		
20	Hsiao, Lee, & Klopfer	2019	In-service teachers	Biology	Adoption	√		√
21	Keiner & Graulich	2020	University	Chemistry	Conceptualizations		√	
22	Keiner & Graulich	2021	University	Chemistry	Conceptualizations			√
23	Krist, Schwarz, & Reiser	2019	Elementary	Biology & physics	Conceptualizations			√
24	Louca & Papademetri-Kachrimani	2012	Kindergartens	Physics & mathematics	Adoption			√
25	Macrie-Shuck & Talanquer	2020	University	Chemistry	Conceptualizations	√		
26	Mathayas, Brown, & Lindgren	2021	Lower secondary	Physics	Conceptualizations			√
27	Mathayas, Brown, Wallon, & Lindgren	2019	Lower secondary	Physics	Adoption			√
28	Moore	2021	NA	Biology	Conceptualizations	√		
29	Moreira, Marzabal, & Talanquer	2019	Upper secondary	Chemistry	Conceptualizations	√	√	
30	Nawani, von Kotzebue, Spangler, & Neuhaus	2019	Upper secondary	Biology	Student		√	√
31	Newman, Coakley, Link, Mills & Wright	2021	University	Biology	Student	√	√	
32	Richards, Elby, & Gupta	2014	In-service teachers	Physics	Student	√		√
33	Robertson & Shaffer	2016	University	Physics	Adoption	√	√	
34	Russ & Hutchison	2006	Elementary	Physics	Adoption	√		
35	Russ, Coffey, Hammer, & Hutchison	2009	Elementary	Physics	Conceptualizations	√		
36	Russ, Scherr, Hammer, & Mikeska	2008	Elementary	Physics	Conceptualizations	√		
37	Scalco, Talanquer, Kiill, & Cordeiro	2018	University	Chemistry	Conceptualizations		√	√
38	Scherr & Robertson	2015	In-service teachers	Physics	Conceptualizations	√		
39	Schwarz, Ke, Lee, & Rosenberg	2014	Elementary	Physics	Student	√		
40	Scott, Anderson, Mashood, Matz, Underwood, & Sawtelle,	2018	University	Biology	Conceptualizations	√	√	
41	Sevian, Hugi-Cleary, Ngai, Wanjiku, & Baldoria	2018	University	Chemistry	Student	√	√	√
42	Southard, Espindola, Zaepfel, & Bolger	2017	University	Biology	Conceptualizations	√	√	
43	Southard, Wince, Meddleton, & Bolger	2016	University	Biology	Conceptualizations	√	√	
44	Speth, Shaw, Momsen, Reinagel, Le, Taqieddin, & Long	2014	University	Biology	Student		√	
45	Stevens, Shin, & Peek-Brown	2013	Lower & upper secondary	Chemistry	Student	√	√	
46	Suarez & Otero	2014	Elementary	Physics	Student			√
47	Talanquer	2010	University	Chemistry	Student	√	√	
48	Talanquer	2018	University	Chemistry	Conceptualizations		√	
49	Tang, Elby, & Hammer	2020	Elementary	Physics	Conceptualizations			√
50	Tate, Ibourk, McElhaney, & Feng	2020	Lower secondary	Biology	Student	√	√	√

Table A1 (Continued). An overview of the selected articles

No	Author(s)	Year	Educational level[1]	Domain	RQ1[2]	RQ2[3]	RQ3[3]	RQ4[3]
51	van Mil, Boerwinkel, & Waarlo	2013	NA	Biology	Conceptualizations			√
52	van Mil, Postma, Boerwinkel, Klaassen, & Waarlo	2016	Upper secondary	Biology	Adoption		√	√
53	Watts, Schmidt-Mccormack, Wilhelm, Karlin, Sattar, Thompson, Gere, & Shultz	2020	University	Chemistry	Conceptualizations		√	
54	Weinberg	2019	Elementary to university students	Physics	Adoption	√		
55	Weinberg (a)	2017	Elementary to university students	Physics	Adoption			√
56	Weinberg (b)	2017	Elementary to university students	Physics	Adoption	√		√
57	Weinrich & Talanquer	2016	University	Chemistry	Student	√	√	√
58	Wilkerson, Shareff, Laina, & Gravel	2018	Elementary	Physics	Adoption	√		√
59	Wilkerson-Jerde, Gravel, & Macrander	2015	Elementary	Biology	Adoption		√	√
60	Zotos, Tyo, & Shultz	2021	In-service teachers	Chemistry	Student	√	√	

Note. NA: Not specified; Conceptualizations: The studies (N:30) providing conceptualizations of MR; Adoption: The studies (N:13) making use of the conceptualizations of MR provided by the 30 studies; Student: The studies (N:17) that do not provide conceptualizations of MR but exemplifying students who either exhibited MR or those did not; & √: Studies that are assigned to research question (RQ) 2, 3, or 4

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