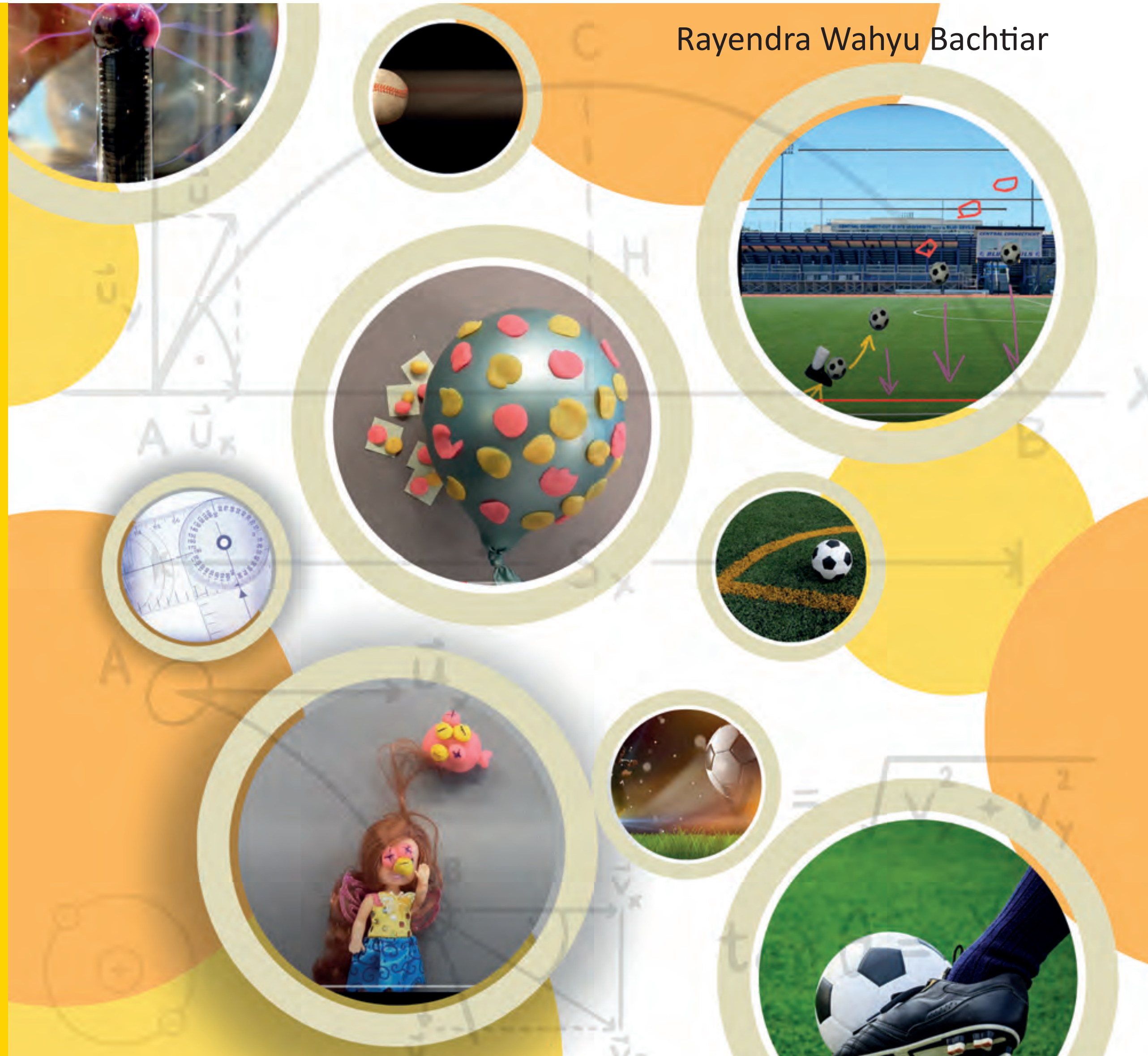
ANIMATED REASONING

Supporting students' mechanistic reasoning in physics by constructing stop-motion animations

Rayendra Wahyu Bachtiar



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Supporting students' mechanistic reasoning in physics by constructing stop-motion animation

Rayendra Wahyu Bachtiar

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ANIMATED REASONING

Supporting Students' Mechanistic Reasoning in Physics by Constructing Stop-Motion Animations

Geanimeerd redeneren

Het ontwikkelen van mechanistisch redeneren binnen de natuurkunde door leerlingen stop-motion animaties te laten maken

Penalaran yang dianimasikan

Membangun penalaran mekanistik siswa melalui membuat animasi stop-motion

(met een samenvatting in het Nederlands)
(dengan ringkasan dalam Bahasa Indonesia)

Proefschrift

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door

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Table of contents

CHAPTER 1 General introduction

1. Introduction

There has been a long-standing call for scientific literacy, a term first coined by Hurd (1958). One of the rationales lies in the vision that scientific literacy for general citizens is crucial in dealing with science-related issues, such as climate change, energy, and health security. Feinstein (2011) refers to scientifically literate people as “competent outsiders” to science. Evidently, science education plays a central role in responding to such a global call. Indeed, scientific literacy is seen as a desired outcome of science education reforms (DeBoer, 2000).

In contrast to the perceived importance of scientific literacy (e.g., DeBoer, 2000; Laugksch, 2000; van Eijck & Roth, 2010), there is no “clear consensus about which aspects of scientific literacy are most salient or important. Different aspects may be more or less important depending on the context.” (National Academies of Sciences, Engineering, 2016; p.2). However, one of the common aspects in the fundamental sense of scientific literacy is engagement in scientific practices.

The Framework for K-12 Science Education proposes eight types of scientific practices essential for the K-12 science curriculum (National Research Council, 2012). One of them is to engage students in constructing scientific explanations. The framework defines scientific explanations as

> “accounts that link scientific theory with specific observations or phenomena – for example, they explain observed relationships between variables and describe the mechanisms that support cause and effect inference about them” (National Research Council, 2012; p.67)

The present study on constructing scientific explanations focuses on one type of causal reasoning, i.e., mechanistic reasoning (MR). The aim is to promote students’ mechanistic reasoning (MR), engaging them in scientific practices, thereby fostering students’ scientific literacy.

2. Student-generated mechanistic reasoning (MR)

Mechanistic reasoning (MR) can be considered one form of causal reasoning. However, MR “involves more than noting which causes are associated with which effects” (Russ et al., 2008; p.506). MR necessarily includes a mechanism that describes the process by which causes bring about effects. Such a mechanism needs to specify activities of (un)observable entities and the interaction between them (Braaten & Windschitl, 2011; Haskel-Ittah, 2022).

Consider as an example the case of two students explaining a well-knows phenomenon in electrostatics: “An inflated balloon will stick to a wall after this balloon has been rubbed against someone’s hair.” When asked to explain this phenomenon, students may come up with very different answers:

Student 1	“When the balloon is being rubbed against the hair, the balloon is attracted to the wall.”

Student 2 “When the balloon is being rubbed against hair, electrons from the hair move to the balloon. As a result, because the charge of an electron is negative, the balloon now becomes negatively charged.”

Student 2’s explanation exhibits MR because this explanation depicts a mechanism underlying the phenomenon (i.e., the balloon is being rubbed). The mechanism contains entities, i.e., electrons, engaging in an activity, i.e., moving from the hair to the balloon. In contrast, Student 1’s explanation cannot be classified as MR. Even though the explanation involves (observable) entities, the student does not specify activities.

Research shows that evoking or eliciting MR in students is challenging. Evidently, for this to happen, some level of domain-content knowledge is necessary (Balabanoff et al., 2020; Hammann & Brandt, 2022; van Mil et al., 2016). However, even if students have been introduced to relevant knowledge, they often resort to simple explanations, such as redescriptions of the phenomenon, such as in the example above (Crandell et al., 2019; Newman et al., 2021; Weinrich & Talanquer, 2016). Moreover, students can use a variety of reasoning approaches (not limited to MR), e.g., teleological reasoning, to explain reaction mechanisms in organic chemistry (Dood & Watts, 2022), or causal reasoning without considering the mechanisms underlying these relationships (Tang et al., 2020).

Due to these challenges, it cannot be assumed that students will automatically provide MR when reasoning about a phenomenon. As in many other areas of education, support is needed. Many studies propose support for students to build MR, e.g., guidance for directing students to construct MR (Krist et al., 2019), and designing a learning approach facilitating students to develop MR (Crandell et al., 2019; Nawani et al., 2019; Sevian et al., 2018). Our study, in accordance with a number of studies (e.g., Andrade et al., 2021; Wilkerson-Jerde et al., 2015; Wilkerson et al., 2018), focused on student-generated models, as a way to stimulate students to use MR when reasoning with their own model creation.

3. Student-constructed models

Many educational researchers advocate the value of student-constructed models to enhance learning. While some offer theoretical perspectives as the rationales for the value (e.g., Ainsworth et al., 2011; Prain & Tytler, 2012; van Meter & Firetto, 2013), others provide empirical evidence (e.g., Tytler et al., 2020). Studies point out that learning by constructing models can be effective. For example, Chang et al. (2010) note that learning by constructing animations results in higher learning gains, provided the construction process is coupled with peer evaluation. Cromley et al. (2019) studied the effectiveness of self-generated drawing as a simple modeling tool.

In order to reap the benefits of learning by model construction, the use of a modeling tool needs to consider student age groups and subject matter. Modeling tools that do not require knowledge of programming code or mathematical formalisms, e.g., paper-based drawings, are more likely to benefit younger students or novice modelers.

However, drawing-based models are less appropriate to represent dynamic processes. Thus, in our study, we utilized a modeling tool that does not need to use explicit modeling rules and can be used to visualize a dynamic process, that is, stop-motion animation (SMA).

4. Student-constructed stop-motion animations

In the days of yore, animators used analog film to create a stop-motion animation (SMA). Today, however, students of all ages can create an SMA with relative ease using ubiquitous software. In addition, freeware SMA applications are widely available and can be accessed on any device, such as computers, tablets, or smartphones.

Constructing an SMA entails building models that involve any physical material (e.g., play dough clay, cut-outs, or other 2D/3D materials), moving these models gradually, and taking pictures of each movement, so that the resulting product gives the impression of movement. For example, in the SMA depicted in Figure 1, two-color clay is used to represent electrons and protons on small pieces of paper and a balloon. The paper is moved gradually and each move is pictured, thus illustrating the pieces of paper moving toward the balloon.

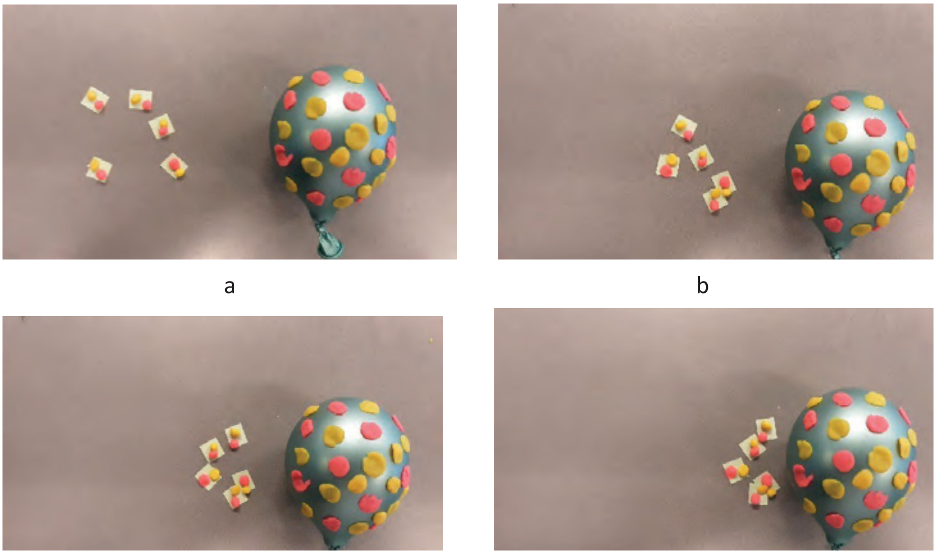


Figure 1. Screenshots of four consecutive frames itn an SMA illustrating electrically charged little pieces of paper moving toward a charged balloon.

Educational research on student-generated SMA as a modeling tool has been conducted in many subjects, e.g., biology (Orraryd & Tibell, 2021), geology (Mills et al., 2019), chemistry (Berg et al., 2019), and physics (Bachtiar et al., 2021), and at many educational levels, e.g., pre-service teachers programs (Hoban & Nielsen, 2013; Nielsen et al., 2022), university students (Berg et al., 2019; Deaton et al., 2013), secondary students (Mills et al., 2019; Orraryd & Tibell, 2021), and primary students (Brown et al., 2013; Fridberg & Redfors, 2018). A review on SMA in science education by Farrokhnia et al. (2020) showed that students-constructed SMAs promote deep learning, and suggested further empirical studies in order to gain comprehensive understandings of the effectiveness of such learning approach.

Research on student-generated SMAs has been conducted extensively by Hoban and colleagues (e.g., Hoban, 2007, 2020; Hoban et al., 2011; Hoban & Nielsen, 2012; Nielsen et al., 2022; Nielsen & Hoban, 2015). The researchers reported on the benefits of engaging students in the process of constructing *slowmation*, (an abbreviation of "Slow Animation"), such as fostering students' conceptual understandings (Nielsen & Hoban, 2015), deeply engaging students with science content (Hoban, 2020; Hoban & Nielsen, 2013), facilitating student discussions (Hoban & Nielsen, 2014), and helping students construct scientific explanations (Hoban et al., 2011; Nielsen et al., 2020). Building on the work by Hoban, Mills and colleagues found that constructing SMA contributed to students' development of conceptual understanding (Mills et al., 2019), and students' interest in learning science (Mills et al., 2020). Other studies pointed to the benefit of constructing SMAs for helping students understand science content (Berg et al., 2019; Orraryd & Tibell, 2021), advancing students' communication skills (Deaton et al., 2013; Fridberg & Redfors, 2018), and making science learning fun for students (Kamp & Deaton, 2013; Vratulis et al., 2011).

Hoban and colleagues point out that students' gain from the construction of SMAs can be optimized by explicitly addressing five stages resulting five different products, i.e., (1) research notes, (2) storyboards, (3) models, (4) digital photographs, and (5) the narrated animation. Each stage has a specific affordance that encourages students to think about the content in different ways (see Hoban et al., 2011; Hoban & Nielsen, 2013). Basically, the actual creation of an SMA starts from Stage 2 and is followed by the subsequent stages. Especially Stages 2 – 4 bring out the nature of SMA construction, i.e., the process of chunking and sequencing (Hoban et al., 2011). Chunking refers to a process "to break a target concept down into its constituent elements or ''chunks,'' while sequencing attends to a process whereby "each chunk then needs to be placed in a sequence to bring the anticipated actions and explanations into a coherent order" (Hoban et al., 2011; p. 996). Thus, our studies focus on chunking and sequencing as essential strategies for constructing SMA. We also argue that chunking and sequencing elicit particular cognitive processes that involve MR, including thinking about entities and activities of entities. Therefore, our studies sought to understand whether and how the construction of SMA, i.e., chunking and sequencing, contributes to supporting students in developing MR.

5. Our research on supporting MR through student-constructed SMAs

We conducted four separate studies to seek to address the main research question:

> *How can student-constructed stop-motion animations (SMAs) be used as a pedagogical approach to support students in developing mechanistic reasoning (MR)?*

In the first study (Chapter 2), we sought to find out what is known about MR in science education research. To do so, we reviewed science education studies that included MR as a focus of their research. This literature study was concerned with four research questions: (1) what are the common aspects of conceptualizations of MR as proposed in the reviewed literature?, (2) why is MR considered to be important for science education, (3) which difficulties do students encounter while generating MR, (4) which strategies have been used to support students in generating MR? This literature review gave us insight into how we could support students in developing MR together with taking into account the challenges and difficulties involved.

The second study (Chapter 3) concerns a case study in a laboratory setting. We chose this approach because the goal of our second study was to get a deep insight into how engaging students in constructing an SMA stimulated them to use MR to explain a physical phenomenon. This study was applied to the physics topic of parabolic motion. Although this topic was considered to be challenging for students (Church et al., 2007), this phenomenon was macroscopically visible and students could explain it using their everyday language. In addition, this study focused on identifying whether the concepts used for students to explain the phenomenon corresponded to the elements of MR, rather than on a scientifically correct concept.

As a follow-up to the second study providing the first insight into how SMA induces MR, the third study (Chapter 4) aimed to gain a comprehensive understanding of why and how student-constructed SMAs contributed to promoting MR. We address this question theoretically and empirically. As theoretical perspective, we propose a theoretical framework illustrating how the construction nature of SMA works in promoting the elements of MR. We examined the extent to which this framework was in line with empirical evidence in terms of a multiple-case study involving small samples. In addition, this case study was applied to a physics topic inherently requiring students to think at microscopic levels, i.e., electrostatic phenomena. This third study could then contribute to generating implications for what to consider when implementing the construction of SMAs as a pedagogical approach in a classroom.

In the fourth study (Chapter 5), we scaled up and translated the context of the third study to a classroom setting. To do so, we collaborated with physics teachers to set up a lesson on static electricity at an international school in the Netherlands. In this study, we examined the characteristics of students-created SMAs and linked them to students' MR, enabling us to understand the conditions under which SMA creation is valuable to MR. The analysis of the data set collected during the lesson also provided valuable insight into how student-constructed SMAs as a pedagogical approach could be implemented in a classroom to support students’ development of MR.

In Chapter 6 we return to the main research question of this thesis by drawing some general conclusions based on the outcomes of the four separate studies.

CHAPTER 2 Mechanistic reasoning in science education: A literature review

This chapter is based on:

Bachtiar, R. W., Meulenbroeks, R. F. G., & van Joolingen, W. R. (2022). Mechanistic reasoning in science education: A literature review. *Eurasia Journal of Mathematics, Science and Technology Education*, *18*(11), em2178. https://doi.org/10.29333/ejmste/12512

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 synthesised 60 science education studies on MR published from 2006 to 2021. The findings showed three common aspects of conceptualisations 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 categorised: (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

1. 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 (National Research Council, 2012; NGSS Lead States, 2013). 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 behaviour 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 conceptualisations 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, Duncan, Vázquez-Ben, et al., 2020; van Mil et al., 2016), and chemistry (Caspari, Kranz, et al., 2018; 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) synthesised existing frameworks for capturing MR, including Russ et al.’s (2008) study, to develop heuristics for MR emphasising 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, Kranz, et al., 2018; Caspari, Weinrich, et al., 2018).

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 synthesise the literature on MR in science education. The central questions for this literature review were:

1. What are the common aspects of conceptualisations 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.

2. Method

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

2.1. Literature search

The literature search started with searching for relevant articles in two databases: Scopus and Web of Science. We recognise 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 2006-2021 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.

2.2. 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 conceptualisations of MR, or (2) made a clear distinction between students who exhibited 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.

2.3. 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 scrutinised 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 these categories in writing, (4) the resulting text was discussed with all authors, revised and reviewed, until full agreement was reached. The appendix lists all reviewed studies and their contribution to the answer to each research question.

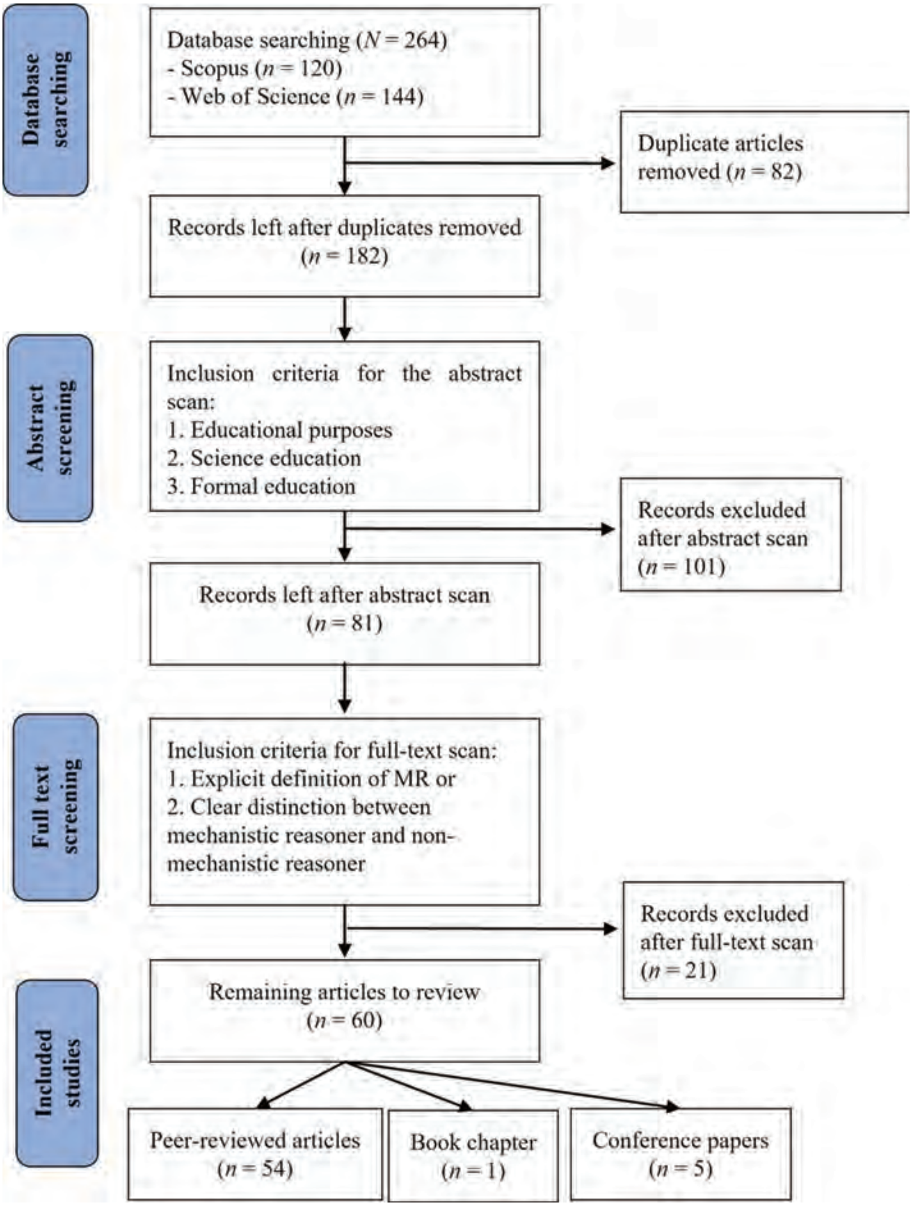


Figure 1. Literature search and selection process

3. Results

3.1. Descriptive overview of the reviewed studies

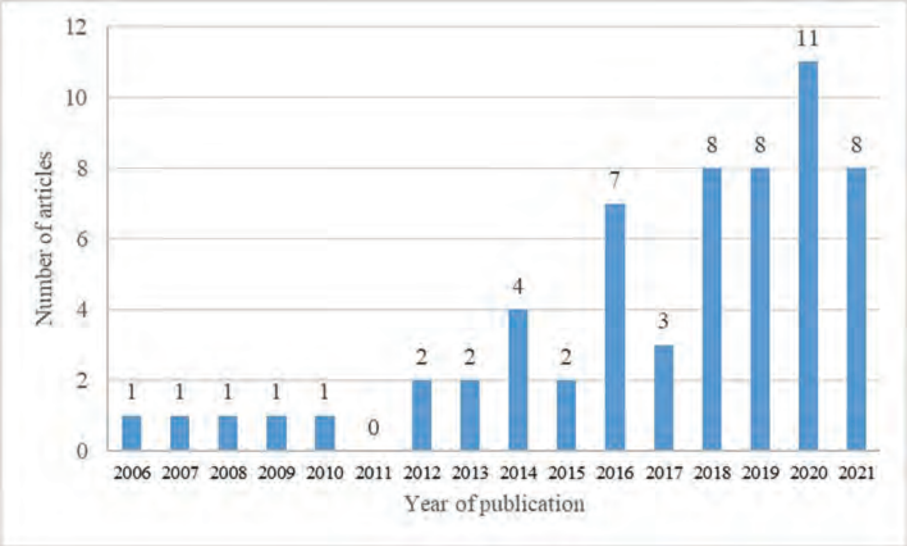


Figure 2. The distribution of the reviewed studies by year of publication

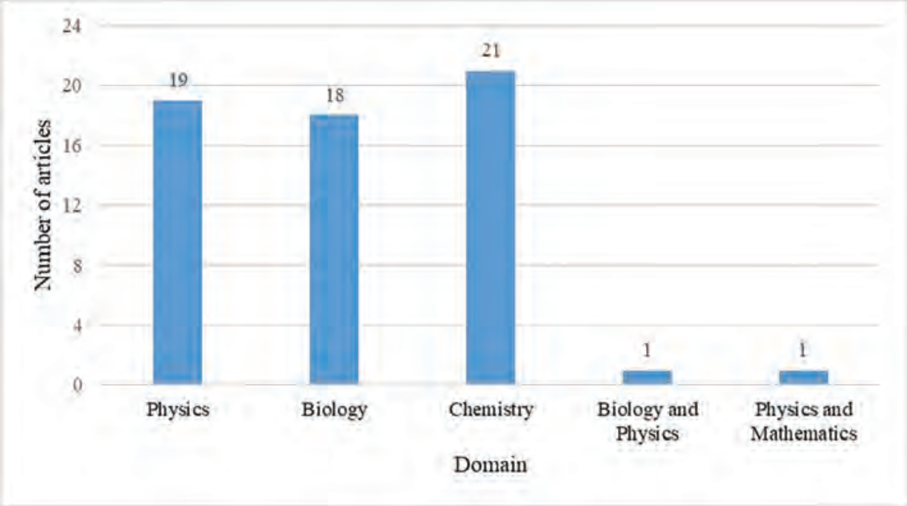


Figure 3. The distribution of the reviewed studies by year of domain(s)

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. 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.

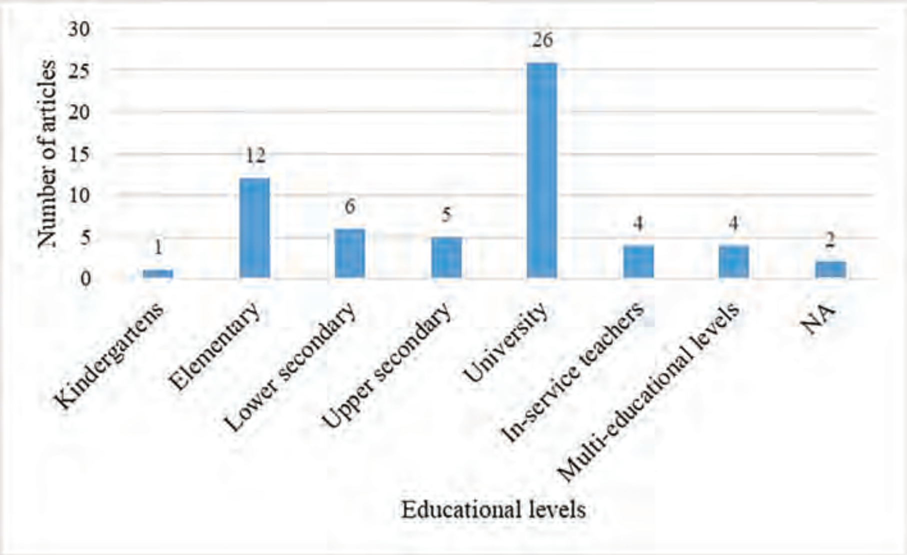


Figure 4. The distribution of the reviewed studies by year of the educational level of the research participants

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

3.2. RQ1: What are the common aspects of conceptualisations 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 conceptualised MR, 13 referred to the conceptualisation of MR provided by one or more of these 30 studies, and 17 studies did not provide conceptualisations 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). Synthesising the commonalities and differences in conceptualisations of MR provided by the 30 studies resulted in three common aspects of conceptualisations 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).

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

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, Kranz, et al., 2018; Cooper et al., 2016; Crandell et al., 2019, 2020; de Andrade et al., 2021; Dickes et al., 2016; Haskel-Ittah, Duncan, & Yarden, 2020; Haskel-Ittah, Duncan, Vázquez-Ben, et al., 2020; 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, Kranz, et al., 2018; Crandell et al., 2019, 2020; de Andrade et al., 2021; Dickes et al., 2016; Haskel-Ittah, Duncan, & Yarden, 2020; Haskel-Ittah, Duncan, Vázquez-Ben, et al., 2020; 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	The same studies as aspect 1

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 emphasise 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 and colleagues (Craver & Darden, 2001; Machamer et al., 2000) defining the concept of mechanisms, i.e.,

> 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. (Machamer et al., 2000, 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 organisation of entities, (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 organisation 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, Duncan, & Yarden, 2020; 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, Duncan, Vázquez-Ben, et al. (2020) 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 the reaction, i.e., “proton transfer or movement of electrons” (Cooper et al., 2016, p. 1705). Also, Scott et al. (2018) reveal 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: (a) related direction, (b) intermediary related direction, (c) rotation, (d) lever arms, (e) constraint via fixed pivot, and (f) 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 conceptualisation 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, Duncan, & Yarden, 2020; 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).

3.3. 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, Duncan, & Yarden, 2020; 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, Kranz, et al., 2018) and to draw correct mechanistic arrows for chemical reactions (Caspari, Weinrich, et al., 2018; 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).

Table 2. The studies discussing the importance of MR

Category	Number of studies	Studies
1. Demonstrating deep conceptual understanding	15	(Balabanoff et al., 2020; Bolger et al., 2012; Caspari, Weinrich, et al., 2018; 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, Duncan, & Yarden, 2020; 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, Kranz, et al., 2018; Caspari, Weinrich, et al., 2018; 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)

Category	Number of studies	Studies
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

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 categorised 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, Duncan, & Yarden, 2020; 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, Duncan, and Yarden (2020), 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.

3.4. 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 categorised 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	Number of studies	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, Duncan, Vázquez-Ben, et al., 2020; 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, Kranz, et al., 2018; 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)

3.4.1. 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, (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, Duncan, Vázquez-Ben, et al., 2020; 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, Duncan, Vázquez-Ben, et al. (2020) 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.

3.4.2. Assigning associated activities to entities

Students demonstrating MR not only recognise 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: (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 categorised as what was called 'Emerging mechanistic frame' rather than MR, since the students recognise 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 recognised 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.

3.4.3. 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.

3.5. 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.

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

Types of support	Number of studies	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; 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)

3.5.1. 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 behaviours of two aluminium foil objects and asked them to explain how these different behaviours 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 (Andrade et al., 2021; Bachtiar 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.

3.5.2. 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, (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.

3.5.3. 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) emphasising 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.

3.5.4. 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 behaviour (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 kinaesthetic activities, was used with group 1, in which the students acted as gas particles to model the behaviour 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' behaviour 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 utilising 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.

3.5.5. 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 mechanistic reasoning 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.

3.5.6. 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.

4. Discussion and Conclusion

4.1. RQ1: What are the common aspects of conceptualisations of MR as proposed in the reviewed literature?

Through synthesising the commonalities and differences in conceptualisations 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).

4.2. 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 practise. 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.

4.3. 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 demonstrated 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).

4.4. 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.

5. 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 recognise 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 recognise 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 characterised 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, Weinrich, et al., 2018; Haskel-Ittah, Duncan, Vázquez-Ben, et al., 2020; 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 emphasised 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, Weinrich, et al. (2018) 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.

CHAPTER 3 Stimulating mechanistic reasoning in physics using student-constructed stop-motion animations

This chapter is based on:

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

Abstract

This article reports on a case study that aims to help students develop mechanistic reasoning through constructing a model based stop-motion animation of a physical phenomenon. Mechanistic reasoning is a valuable thinking strategy for students in trying to make sense of scientific phenomena. Ten ninth-grade students used stop-motion software to create an animation of projectile motion. Retrospective think-aloud interviews were conducted to investigate how the construction of a stop-motion animation induced the students’ mechanistic reasoning. Mechanistic reasoning did occur while the students engaged in creating the animation, in particular *chunking* and *sequencing*. Moreover, all students eventually exhibited mechanistic reasoning including abstract concepts, e.g., not directly observable agents. Students who reached the highest level of mechanistic reasoning, i.e., chaining, demonstrated deeper conceptual understanding of content.

Keywords

Mechanistic reasoning, stop-motion animation, modeling, physics, classical mechanics

1. Introduction

Mechanistic reasoning has been found to be a powerful thinking strategy for students trying to make sense of phenomena by explaining the processes underlying cause-effects relationships through involving causal agents, “entities,” and their action, “what entities do” (Krist et al. 2019; Machamer et al. 2000; Russ et al. 2008). For example, considering the question “Why does an ice cube melt?”, two hypothetical answers may be given by students:

Student A says that “heat makes an ice cube turn into liquid water”; Student B states that “while heating an ice cube, water molecules are moving faster and they break the hydrogen bonds between molecules and eventually these molecules separate, thus forming liquid water.”

Student A’s statement conveys a particular cause (heat) and an effect (liquid water) without considering how the cause brings about the effect. Student B’s explanation provides processes underlying such causality through including a *mechanism* in terms of unobservable causal agents, *entities* (water molecules) and what these entities do (an *activity*), i.e., “moving faster” and “break hydrogen bonds,” to enable the ice to become liquid water. This makes Student B’s explanation a mechanistic one.

A number of studies have demonstrated the value of mechanistic reasoning in promoting students’ understanding of concepts (Bolger et al. 2012; Southard et al. 2016; Talanquer 2018). For example, Southard et al. (2016) revealed that mechanistic reasoning was needed to understand molecular mechanisms in connecting genes to traits. Some studies consider mechanistic reasoning as a worthy thinking strategy for developing so-called “good” scientific explanations (Braaten and Windschitl 2011; de Andrade et al. 2019; Talanquer 2010). Braaten and Windschitl (2011) defined good scientific explanations as *Explication, Causation, or Justification*. Mechanistic explanations can provide such causation. A study by de Andrade et al. (2019) noticed that the students who involved unobservable agents, “particles of air,” and the behavior of these particles, “move faster,” were able to explain why an increase in the temperature of a gas effected an increase in the pressure of that gas.

However, incorporating relevant entities and how these entities engage in particular behavior to give rise to a phenomenon is reported to be especially difficult (de Andrade et al. 2019; Haskel-Ittah et al. 2020; Schwarz et al. 2014; Speth et al. 2014; Visintainer and Linn 2015). For example, Speth et al. (2014) noticed that students’ explanations of evolution failed to incorporate molecular entities, such as DNA and genes, even after instruction, leading to non-mechanistic explanations. Another study documented that even though the students were aware of human factors, as causal agents responsible for global climate change, their explanations failed to explain how the human action warmed the earth (Visintainer and Linn 2015). Schwarz et al. (2014) showed that even though students recognized the existence of water molecules, their explanations of evaporation were still not mechanistic due to the absence of activities of these entities bringing about evaporation.

In view of the difficulty in promoting mechanistic reasoning, there is a need to support students in building such reasoning. In this study, we investigated one potential support: using the creation of stop-motion animations (SMA) as a modeling tool. By creating and ordering multiple images of a process and sequencing these in the correct order we contend "chunking and sequencing", the nature of SMA, can be a support for students' mechanistic reasoning. To model a phenomenon using stop-motion animation, students need to construct a series of frames representing the underlying process of the phenomenon. Creating each frame requires thinking about a step in the process. When all frames are arranged in sequence, students need to think about a coherent story representing the underlying process of the phenomenon, thus leading to the use of mechanistic reasoning. The goal of this study is, therefore, to investigate how engaging the students in constructing a SMA induces their mechanistic reasoning. In particular, the present study focuses on answering the following research questions:

RQ1: To what extent are 9th grade students able to model a phenomenon in classical mechanics using stop-motion animation?

RQ2: To what extent do the students use mechanistic reasoning while discussing their stop-motion animations?

2. Background

2.1 Computer-Based Modeling

There has been considerable literature advocating learning science through creating models by drawing (Ainsworth et al. 2011; Bollen & Joolingen, 2013; Heijnes et al., 2018; Prain & Tytler, 2012; van Joolingen et al., 2015), programming (Louca and Zacharia 2012; Wilensky and Reisman, 2006) or stop-motion animation (SMA) (Farrokhnia et al., 2020; Hoban and Nielsen 2012; Wilkerson-Jerde et al. 2015). The resulting scientific models can be static, such as pictures, diagrams, graphs, equations; or they can be dynamic, e.g., video, animation, simulation (Gilbert and Justi 2016). Ryoo and Linn (2012) found that dynamic visualizations were more effective than static illustrations to depict dynamic processes, such as chemical reactions during photosynthesis. In another example, in order to build a model about the marine ecosystem with complex species behavior, dynamic representations were more suitable than static ones (Papaevripidou et al. 2007). Chang et al. (2014) also found that Chemation, a drawing tool, supported the students in visualizing their understanding about a dynamic aspect of a chemical reaction, such as how atoms moved and broke chemical bonds, with ease. An adequate modeling tool should thus ideally support student-constructed dynamic models.

Currently, existing computer modeling tools, such as Stagecast Creator, SimSketch, and SiMSAM, have been employed in many educational studies on student-constructed dynamic models (Bollen & Joolingen, 2013; Heijnes et al., 2018; Louca et al. 2011; Louca and Zacharia, 2008; Wilkerson-Jerde et al. 2015; Wilkerson et al. 2018). Louca and Zacharia (2008) compared two programming-based tools, i.e., Stagecast Creator and Microworld Logo. StageCast employs a visual, agent-based modeling language whereas

Microworld Logo is based on programming code. Where the first is quicker in creating the model, Louca et al. (2011) noticed that the students employing Stagecast Creator to construct a model of accelerated motion engaged in unproductive modeling discourse. That is, during the modeling process the students struggled to include a programming rule that could represent accelerated motion.

The use of the latter two modeling tools above requires some formal representation of the model. This may be a drawback, especially for younger students. Sins et al. (2005) suggested that novice modelers employ qualitative graphical models, not requiring formal coding. Bollen and Joolingen (2013) present a drawing-based modeling tool, SimSketch, which provides more informal ways of constructing models, with freehand drawings as input, and not requiring programming language. A study by van Joolingen et al. (2015) showed that SimSketch supported the students in creating a model of solar eclipses. In another study, Heijnes et al. (2018) found that by using SimSketch to model evolutionary processes the students engaged in complex reasoning, as long as a sufficient level of scaffolding was provided.

All modeling tools discussed above, however, require the specification of explicit rules, in the form of code or as visual representations. In this study, we look at a way of modeling without explicit specification of model rules: stop-motion animation (SMA). With the advance of computer technologies, it is possible for students to design a SMA themselves with relative ease. SMA is a form of animation created from a series of individual images, called frames. Like a common animation, SMA can be used to visualize events changing over time. The construction of a SMA involves two essential strategies: *chunking* and *sequencing* (Hoban and Nielsen 2010). For example, to animate a process, it has to be broken down into a number of single steps, called *chunks*, and each step is represented in one or a small number of frames. All frames are sequenced in such a way that each frame looks like an alteration of the previous one. Thus, when these frames are played back, they appear to display the process in a continuous way.

A recent literature study reports on the benefits of SMA (Farrokhnia et al., 2020). In another study, Nielsen and Hoban (2015) found that after creating a SMA pre-service teachers gained more understanding of the moon phases than before the animation construction. Also, learning through creating a SMA afforded students opportunities to generate discussion (Hoban and Nielsen 2014; Mills et al. 2019). Mills et al. (2019) noticed that the construction of a SMA engaged students in resolving conflicting ideas by generating dialogue with their teacher. Other studies highlight SMA can contribute to students' mechanistic reasoning (Wilkerson-Jerde et al. 2015; Wilkerson et al. 2018).

2.2 Reasoning mechanistically with Stop-Motion Animation

Explaining a phenomenon mechanistically means to provide an account of why and how the phenomenon can occur in terms of *Entities* and *Activities* of these entities. Apart from these two elements, Russ et al. (2008) extended this view by introducing seven elements of mechanistic reasoning in a hierarchy, representing the level of sophistication: (1) the target phenomenon, (2) setup conditions, (3) entities, (4) activities of entities, (5) properties of entities, (6) organization of entities and activity and (7) chaining. *Entities* are elements or agents playing a role in producing a phenomenon. *Activities* are what *entities* do to come up with a phenomenon. For example, in the phenomenon above about a melting ice cube, water molecules are an *entity*. “Moving faster” is an *activity* of those entities. Chaining, as the highest level of mechanistic reasoning, is a causal structure that make a claim about why and how a phenomenon can occur. This causal structure represents a specific condition that would occur if entities engaged in specific activities. For instance, in the phenomenon about a melting ice cube, the statement “the water molecules eventually separate, thus forming liquid water” indicates the presence of chaining.

Krist et al. (2019) argued that mechanistic reasoning required identifying relevant factors at a scale below the level of the observed phenomenon, e.g., unobservable entities. However, mechanistic explanations of physical phenomena do not always involve invisible factors, such as system levers (Bolger et al. 2012) and accelerated motion (Louca et al. 2011). In this study, we paid attention to the way students conceptualize their abstractions of these factors in terms of a concrete and an abstract level. Consider two objects: “a ball” and “a molecule.” In this study, we consider both these entities to be of a *concrete* nature as both are in principle observable, albeit on a different scale level. Abstract entities include constructs that are not observable or *theoretical*, even in principle, such as force or a gravitational field. Only the consequences of their presence may be observable. For an entity “gravity,” there may be an associated activity, “pull down”.

As discussed above, several studies employed a SMA as a modeling tool to support science learning, but only a few studies focused on the development of mechanistic reasoning, e.g., Wilkerson-Jerde et al. (2015) and Wilkerson et al. (2018) who studied reasoning about the spread of “smell”. Even though these studies clearly demonstrate the occurrence of mechanistic reasoning during the construction of an SMA, the way in which the construction of an SMA affects students’ thinking has gone largely unnoticed. Farrokhnia et al. (2020) suggest further study to investigate students’ thinking during the construction process of SMA. One way to uncover the effect of the construction of SMA on students’ thinking is by examining students’ reasoning behind the main processes in this construction process: chunking and sequencing. We contend that building sequential chunks leads students to think in terms of *entities* and the *activities* of *entities*. Other mechanistic elements may also be called upon to make a coherent sequence. This means that by unveiling students’ reasoning behind the process of *chunking* and *sequencing* we can gain insight into how constructing SMA works in inducing students to think in mechanistic ways.

3. Method

3.1 Study Context

A qualitative case study was used for obtaining a better understanding of how and why students’ reasoning occurred throughout the creation of a stop-motion animation (Creswell and Poth 2018; Yin 2013). This study involved ten ninth-grade students (5 males and 5 females; 15 – 17 years old) from an international secondary school located in a large city in the Netherlands. Before the students took part in the study, a letter of consent from their parents had been obtained.

3.2 Modeling Tasks and Data Collection

In this study, a task-based one-on-one interview approach was conducted in the students' school. The interview was recorded on camera and by voice recording. On-screen activities were recorded using Camtasia screen capture software. Finally, all the student-constructed animation artifacts were collected. The modeling task was performed in the built-in capture program of the HP Sprout computer (Figure 1). The students modeled the motion of a ball after it was kicked by foot. This full task took 60 minutes and the students followed a three-stage procedure:

1. Introduction (10 minutes)

During the first stage, the students were introduced to the basic features of stop-motion animations and the tools used to construct them (Figure 1). The students practiced by creating a simple animation of a car moving in a straight line.

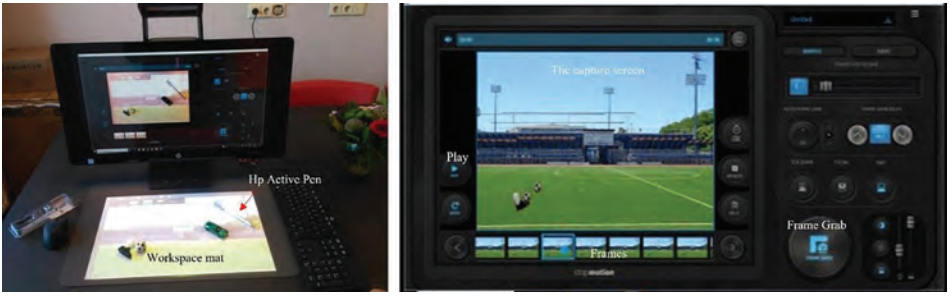


Figure 1. Setup for creating stop-motion animations using a HP Sprout computer

2. Creating the animation (15 minutes)

In the second stage, the students worked in creating the animation presenting motion of the ball. The construction of the animation begun by providing a schematic frame (Frame 1 in Figure 2) with the foot and the ball. The students were then asked to continue creating the next frame, e.g., Frame 2 and 3 in Figure 2. The students were not interrupted during the construction process. Guidance was provided only when they needed technical help.

Figure 2. The first three frames; Frame 1 is a schematic frame

3. Discussion (35 minutes)

To gain insight into the students' cognitive processes, a *retrospective* thinking-aloud was used (Ercikan et al. 2010; Ericsson and Simon 1998) requiring the students to verbalize their thought during the construction process. In prompting them to do so, the students were asked questions like : 1) "In the third frame (Figure 2), why do you think the ball moved here?" and 2) "How could the ball move here (Figure 2; Frame 3)?" Follow-up questions were based on concepts that came up. After the students had explained all frames, a video and a picture displaying the actual movement of a football being kicked by someone were presented. The students were then asked to compare their animation with both the video and the picture and to comment on any observations.

3.3 Data Sources and Analysis

The animations created by the participants and their utterances from audio-video recordings were transcribed and coded using the coding scheme for mechanistic reasoning developed by Russ et al. (2008). Table 1 shows this coding scheme and the example of coded utterances for our context. This coding process also included the students' level of abstraction, meaning how they used concrete-abstract concepts to conceptualize each element of mechanistic reasoning into either abstract or concrete. To validate this coding process, about 10% of the coding was then checked by a second coder from the same institute. Interrater reliability (Cohen's kappa) was found to be 0,79. Coded utterances were displayed in a graph, wherein one graph presented the students' reasoning about each phase of the ball motion, for example the graph in Figure 4.

Table 1. Coding scheme of mechanistic reasoning (adapted from Russ et al. (2008)) and the example of coded utterances.

Mechanistic Aspect	Example of students' excerpts
1. Target Phenomenon (TP) We code the presence of this element in students' utterances when the students describe a particular phenomenon without explaining how and why this phenomenon occurs.	Concrete: "The ball goes up with a straight forward line Abstract: "As the ball goes up, its energy is getting less"
2. Setup Condition (SC) We code the students' statements as the setup condition when the students describe a starting condition that must happen before the particular event runs.	Concrete: "He kicks it with a sort of upward angle (in the first position)" this statement presents the way a football player kicks the ball in the first position to enable the ball to move up in a certain direction. Abstract: "When the foot is kicking the ball, it is transferring energy to the ball, and then this energy is used for the ball to go up" This statement explains the way energy comes up, before the ball uses this energy to move up

Mechanistic Aspect	**Example of students' excerpts**
3. Entity (E) An entity is a causal agent that plays a crucial role in producing a phenomenon. We code for the presence of this element in the students' statements when they try to identify the agents that cause the phenomenon to happen. Those agents that are tangible or visible are classified as concrete concepts, whereas abstract agents are invisble or theoretical	Concrete entity: The foot, the earth Abstract entity: Energy, gravity
4. Activity of entity (AI) An activity is what entities engage in to produce a phenomenon. We code the students' statements as this aspect when the students identify what entities do to give rise to a phenomenon.	Concrete activity: "The foot kicks the ball" Activity is "kick the ball," and Entity is "the foot" Abstract activity: "The foot gives force to the ball" Activity is "gives force," and Entity is "the foot"
5. Property of Entity (PE) An entity has a general *property*. By having this property, the entity could do a specific *activity*. We code students' statement as Property when the students identify any characteristic of an Entity that is necessary for a certain activity.	Concrete property: Air resistance is something that can be touched (Property), so that "…because it needs to push all the particles of air out of your way" Abstract property: "it (the ball) still has *forward momentum* (Property)"
6. Organization of entity and activity (IOE) For a phenomenon to happen sometimes requires a specific condition: spatial organization of entities or temporal organization of activities. We code the students' statements as this aspect when they describe where entities are located (spatial) or how long entities do the activities (temporal).	Concrete: "The ball has only kinetic energy, *when the ball is on the ground*" Abstract: "The ball can go up as long as the energy is stronger than gravity"

Mechanistic Aspect	Example of students’ excerpts
7. Chaining (C) We marked the students’ statements with chaining when their explanations present a cause-effect relationship. This relationship signifies a claim about what *must have happened previously* to bring about the current state of things (backward-chaining) or what *will happen next* given that certain entities and activities are present (forward-chaining). In this study, all students’ chaining is classified as forward-chaining. Also, when students construct a chaining, they involve not only *Entities* and *Activities*, but also other elements of mechanistic reasoning. For example, a chaining consists of *Entities*, *Activities*, *and a Setup condition*. Because the students employ forward-chaining, their statements referring to the *next condition* are used to determine whether chaining is classified as concrete or abstract concepts. For example, “the ball goes up in a straight line, because you kick it with sort of an angle,” the chaining is “the ball goes up in a straight line” and this chaining is concrete.	Concrete: “Because you kick the ball up, *so the ball goes up in a straight line*” Abstract: “As the ball goes up (with a change in the direction), *it loses momentum*.”

4. Results

4.1 Model of the Ball Motion

All students succeeded in creating an SMA representing the motion of the ball resembling a curved trajectory. For instance, Figure 3 displays the animation created by Student A. For analytical purposes, we divided the ball’s motion into three sequential phases (as for example in Figure 3b): (1) Phase A, the initial movement (frame 1, 2 and 3); (2) Phase B, when the ball starts to ascend slower, up to the point where it reaches maximum height (frame 3, 4 and 5); and (3) Phase C, describing the downward motion until the ball reaches the ground (Frame 5, 6, 7 and 8). Table 2 provides the characteristics of each phase extracted from all students’ reasoning and an example of the students’ statements describing these phases, together with concrete and abstract concepts.

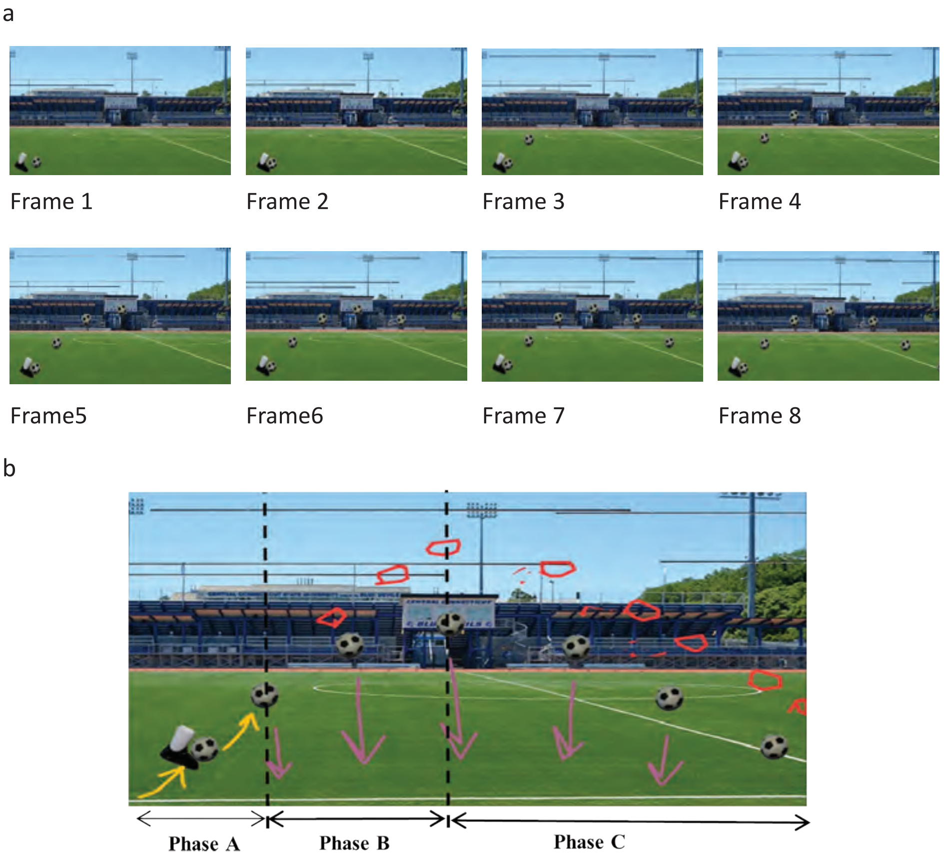


Figure 3. The stop-motion animation representing the motion of the ball created by Student A. (a) a series of eight frames depicting a sequence of moves of the ball; (b) drawings added by the student to the animation to explain it afterwards.

Table 2. The characteristics of Phase A, B and C and the students' reasoning about these phases

Phase	Characteristics	Example of Quote
Phase A	This phase is the initial movement of the ball. The motion immediately after the ball is kicked. This movement is only influenced by the kicking. There is no effect of gravity on this movement. Some students argued that as the ball goes up, the slope is constant.	Concrete concepts: "so you kick it, and it goes there (to the second position in straight line)" Abstract concepts "the person who is kicking the ball, he is giving like the force to the ball [*from the bottom*], that makes the ball go higher (in straight line)"

Phase	Characteristics	Example of Quote
Phase B	This phase is indicated by a change in the slope or the ball starts to change its direction as it goes up. This movement takes place from the moment the slope changes until the ball reaches the highest position. There is an effect of gravity on this movement.	Concrete concepts “when it (*the ball*) is on here (*4th position*), and then it starts decreasing (*goes up with a change in direction*)” Abstract concepts: “yes, because the gravity is like starting to. Because the force that is applied makes the ball goes higher, and then gravity makes the ball, like pull back to the ground, so it is here (*moves up with a change in direction*)”
Phase C	This phase happens when the ball starts going down from the top position until it reaches the ground	Concrete concepts: “this point, at the highest point, it is up all the way, and then it is still in arch in going down (*move down with curved line*)” Abstract concepts: “because the gravity starts, hmm like, the force applied doesn’t enough to continue to go higher, and the gravity starts pulling the object [*the ball*] back to the ground [*goes down from the top*]”

4.2 Mechanistic Reasoning as demonstrated in the reasoning about the animations

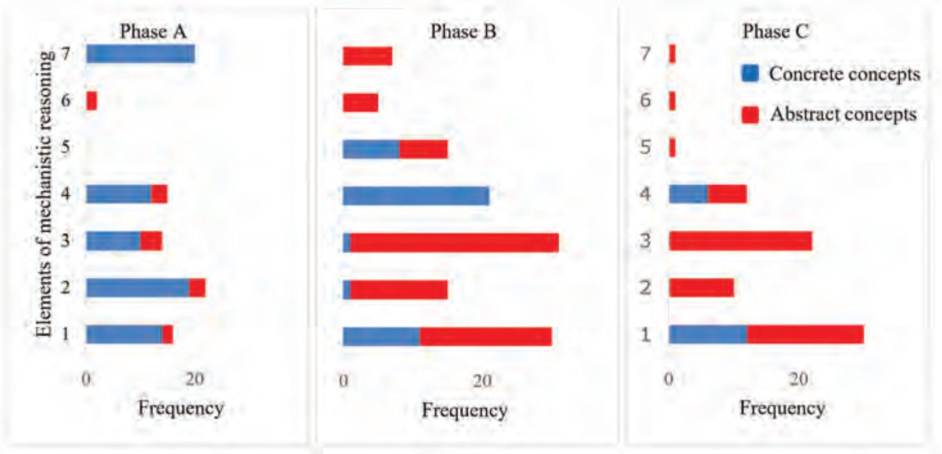


Figure 4. The total number of times each element of mechanistic reasoning together with concrete and abstract concepts is used by ten students to reason about the ball’s motion in each Phase.

Figure 4 represents the combined utterances from all students’ reasoning about the ball’s motion. In general, reasoning about Phase A mostly incorporated concrete concepts. Notably, the use of abstract reasoning became more frequent in Phases B and C. Entities (element 3) and Activities of these entities (element 4) were most prevalent in all phases. As shown in Figure 4, all students did indeed display these two elements in all phases. All students were thus able to generate mechanistic reasoning. In phase A, all students conceived entities as concrete concepts, such as the foot, kicking, and few students invoked abstract entities, e.g., force. In subsequent phases, all students were able to exhibit abstract entities, such as momentum, gravity.

Chaining was prevalent in phases A and B, but this almost disappeared in Phase C (see Figure 4). In addition, the abstraction of chaining and the total number of students reaching chaining differed in all phases. All students could reach chaining in Phase A, but in Phase C only one student could do so. Those students were able to identify entities and were capable of assigning a plausible action to these entities to enable a particular movement of the ball to occur. In the following section, we examine the reasoning in each phase of the ball's motion. We chose two representative students: Student A and Student B. These two students are taken as being representative of a group of the students who employed abstract entities from the start (phase A) and the other students who only started using abstract entities from phase B onwards. Additionally, in Phase C, Student B exhibited chaining, whereas Student A did not.

Phase A

In Phase A, the ball moves upwards, more or less in a straight line. To reason about this motion, the abstractions exhibited by Student A and B differed (see Figure 5). Figure 5 shows that Student B only employed concrete concepts, whereas Student A involved abstract concepts. Both demonstrated concrete chaining.

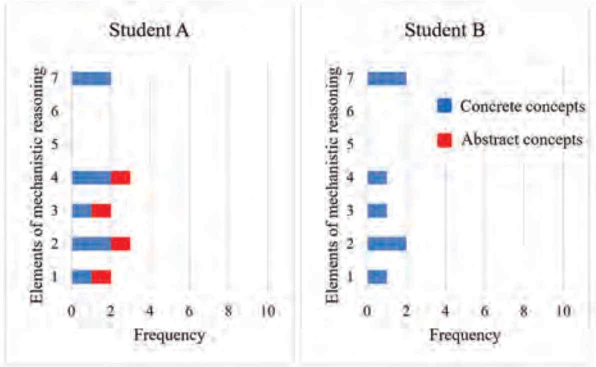


Figure 5. Elements of mechanistic reasoning used by Student A (left) and Student B (right) to reason about Phase A

Student A used the first three frames (see Figure 3a) to depict the ball moving upwards immediately after a kick. She stated that

> *"... because the force is from the bottom [2nd frame; 1st position] ... the person who is kicking the ball, he [the foot] is giving like the force to the ball [Frame 1 and Frame 2], that makes the ball [to] go higher [Frame 3] ... The*

> *foot is kicking the ball like here, from the bottom [she draws a yellow arrow to represent an elevation angle; see Figure 3] which makes the ball [to] go to this position [the second position, she draws a second yellow arrow, which links the first position to the second position, to represent the ball moving up in a straight line]… ".*

The excerpt above conveys Student A who was able to explain the upward motion through generating a chaining involving concrete and abstract entities (element 3), concrete and abstract activities (element 4), and a concrete setup condition (element 2). She asserted that this motion could occur due to the abstract entity "force" that did "make the ball [to] go higher" (element 4; concrete). This entity existed because "the person" (element 3; concrete) who "was kicking the ball" (element 4; concrete) is "giving like the force to the ball" (element 4; abstract). Additionally, she also drew the first yellow arrow (see Figure 3b) to represent a specific direction of kicking (element 2; concrete), indicating an *elevation angle*. Owing to this kicking, the ball could "go to this position [Frame 3]" in a straight line (element 7; concrete) and Student A also drew the second yellow arrow to represent this motion.

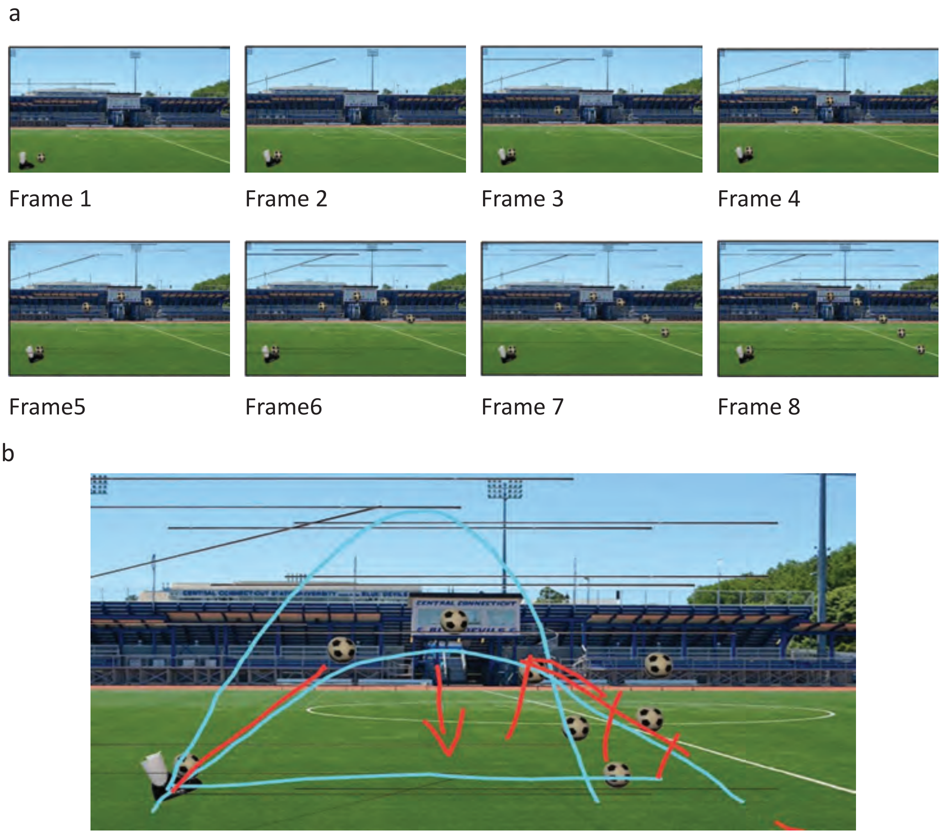


Figure 6. A stop-motion animation representing a model of the ball's motion constructed by Student B; (a) a series of eight frames depicting a sequence of moves of the ball; (b) drawings added by the student to the animation during the explanations.

Regarding the ball's motion in Phase A (see Figure 6), Student B stated that

> *"… because, I can see here [frame 1 and 2], that he kicks it with sort of upward angle, so I see sort of arch, forming… so you kick it [the ball], with sort of the angle [he points to a way of a kick representing the way the foot kicks the ball, namely an elevation angle], that makes it go that way [he draws a red line to represent the ball moving up to the second position in a straight line]…"*

Through concrete chaining (element 7), Student B explained why and how the initial movement of the ball could go up in a straight line (see Figure 6b). This chaining consisted of a concrete entity (element 3), a concrete activity (element 4), and a concrete setup condition (element 2). In Frame 1 and 2 he identified a concrete entity, "he [the foot]," taking an action "kicks the ball" to cause the ball to move up. Additionally, in Frame 2, he also added the particular way of kicking "with sort of the angle" (element 2; concrete), so "that makes it go that way [he draws a red line to represent the initial movement in straight line; see Figure 6b]" (element 7; concrete).

Phase B

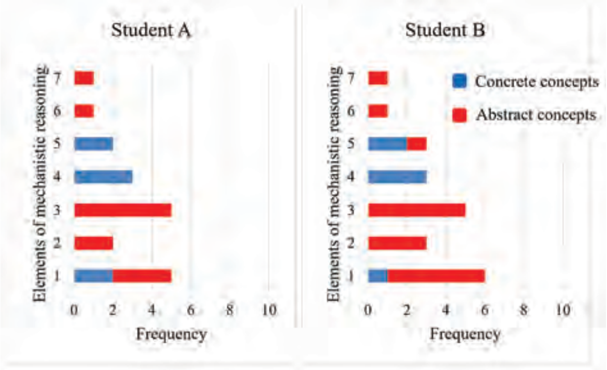


Figure 7. Elements of mechanistic reasoning used by Student A (left) and Student B(right) to reason about Phase B

As shown in Figure 7, the abstraction level used by Student A and B to reason about Phase B appears to be similar. Student B is now also employing abstract concepts:

> *"… after a certain time on air [in the second position; Frame 3], the ball starts to lose its momentum. And that [losing momentum] causes it [the ball] to slow down and a decrease in it [momentum]. hmm by slowing down, it [the ball] doesn't increase as much with its height [he draws a blue line to represent the ball which was moving up in straight line and then its direction changed]… when right from the kick off [Frame 1 and 2], it [the ball] will have a momentum, and it [momentum] will be lost, due to air resistance and gravity trying to pull it [the ball] back down. Since it [the ball] has to go, since it [the ball] is going up [frame 3 to frame 4], it [the ball] slows down, because it needs to push all the particles of air out of your way and also needs to fight the gravity which is very powerful of force…"*

Moreover, Student B was able to use abstract chaining to describe the reason for the change in the direction. Through chaining, he asserted that the abstract entities, i.e., momentum, gravity, and air resistance, played a crucial role in changing the direction. He argued that momentum arising from "right from the kick off" (element 2; abstract) enabled the ball to go up (element 4; concrete). He also identified the activity that gravity engaged in "trying to pull the ball down" (element 4; concrete). Additionally, he considered air resistance to be something that could be touched (element 5; concrete). With this general property of air resistance, this entity could behave and interact with other concrete entities, that is, along upward movement the ball "needs to push all the particles of air out of your way" (element 4; concrete). Additionally, he also contended that an activity of both air resistance and gravity was taking place over the upward movement (element 6; abstract): "also needs to fight the gravity which is very powerful of force". Therefore, as the ball went up, the ball's direction changed, because "the ball starts to lose its momentum, that (losing momentum) causes it (the ball) to slow down and decrease in it. Hmm by slowing down, it (the ball) doesn't increase as much with its height" (element 7; abstract).

Phase C

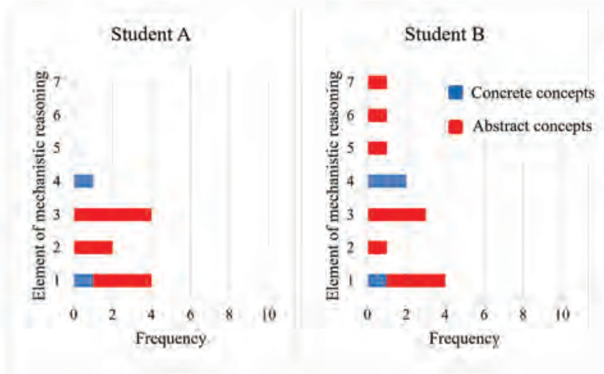


Figure 8. Elements of mechanistic reasoning used by Student A (left) and Student B (right) to reason about Phase C

Figure 8 shows that in Phase C, Student B used chaining whereas Student A did not. Student A constructed Frame 5, 6, 7 and 8 (see Figure 3a) to represent this phase. When explaining the way the ball moved down, Student A began by arguing from a starting condition in the top position (Frame 5) that the ball did not go up anymore. She stated that "*because … the force applied isn't enough to continue to go higher, … the force gets less, and gravity is more strong or more powerful …*" (element 2; abstract). She then pointed out the reason why the ball could go down. She argued that

> *"…because … the gravity starts pulling the object [the ball] back to the ground [from the top position] … the ball gets faster, which increases its kinetic energy. Also, potential energy decreases ….".*

Student A contended that the ball could go down due to gravity (element 3; abstract) taking an action, "pull the ball" (element 4; concrete). Due to a pull by gravity, the ball "gets faster which increases its kinetic energy, also potential energy decreases" as the ball went down. However, she did not explain the reason why the pull of gravity caused the ball to move faster and caused an increase in kinetic energy. In addition, she was unable to explain the reason why the ball could reach the specific position during the downward movement (as shown in Figure 3b). Hence, her statements did not display chaining.

Figure 6 shows Student B's explanation, that started with demonstrating the condition of the ball in the top position (Frame 4) allowing the ball not to go up anymore. He stated that "*because it [the ball] needs kinetic energy to go up (Frame 4). And since it [the ball] ran out (moving up), it [the ball] almost uses its kinetic energy …It [the ball] can't go up anymore, because it [the ball] needs more kinetic energy to do that…*" (element 2; abstract).

Student B then described why the ball could reach the specific position as the ball went down (Frame 5, 6, 7 and 8). He stated that

> *" … so then it [the ball] reaches a peak [the top position; Frame 6], … and then falling … because now it [the ball] is working with gravity … because this [gravity] wants to pull it [the ball] down [he points to the red arrow representing the work of gravity pulling the ball down; Frame 6, 7, and 8]. But it [the ball] still has forward momentum … It [the ball] can't go forward straight, because it [the ball] still has to fight gravity, but it [the ball] is working with gravity, but it [the ball] still has some residual forward momentum. so when you do with that, it is sort of slope down, and angle [the ball moves down gradually], instead of dropping down immediately [he gestures to each position to depict the gradual downward movement] …".*

Student B contended that two abstract entities "momentum" and "gravity" played a role in preventing the ball falling straight down. During downward movement, gravity "pulls the ball down" (element 4; concrete) and the ball has "some residual forward momentum" (element 5; abstract) maintaining horizontal velocity "instead of dropping down immediately" (element 4; concrete). As a result, the ball moved down gradually "*when you do with that, it is sort of slope down, and angle*" (element 7; abstract).

In sum, even though Students A and B started with a different abstraction of reasoning, both exhibited concrete chaining. Both students also used abstract chaining in Phase B. However, Student B was the only one who did so in Phase C. Moreover, there appeared to be an increase in Student B's understanding of the motion. In particular, his conception of entity evolved toward a more scientifically correct use of the concept. In phase B, Student B identified momentum as an entity to enable the ball to move up. In phase C, he conceptualized momentum as a vector "forward momentum."

5. Discussion and Conclusions

The main goal of this study was to investigate how engaging students in constructing SMA could induce mechanistic reasoning. The first research questions was "To what extent are 9th grade students able to model a phenomenon in classical mechanics using stop-motion animation?" We found that all students were able to sequence frames to model a ball motion resembling a curved trajectory. Three distinct phases could be distinguished in each model: the initial upward movement (Phase A), the change in direction (Phase B), and the downward movement (Phase C). Constructing the model using the stop-motion animation required the students to visualize the moment-by-moment motion of the ball and these moments are arranged in order (chunking and sequencing). It was found that the creation of the first moment (Phase A) was mostly attributed to a visible agent "the foot". In the subsequent moments, most of the students started to think about invisible agents. Moreover, the last two moments triggered students to think deeply with content, in particular the usage of abstract concepts.

The second research question was "To what extent do the students use mechanistic reasoning while discussing their stop-motion animations?" The stop-motion animation as a means to model the ball motion supported all students in building mechanistic reasoning, as becomes clear from the presence of entities and activities in all phases. We attribute these to chunking and sequencing to model the ball motion. In Figure 9, we represent how students built mechanistic reasoning through chunking and sequencing. When sequencing the frames, the students needed to identify relevant entities. At the same time, they also thought about plausible activities of those entities to make the plausible move to the next chunk (the next frame). Most of the students incorporated the other mechanistic elements to enable the next move to occur. For instance, in Frame 1 and 2 Student A thought about the specific way an entity, "the foot," kicked the ball (as an activity of the foot) to enable the ball moving up to the second position in a straight line (Frame 3). These findings are in line with previous studies, e.g., Wilkerson-Jerde et al. 2015; Wilkerson et al. 2018, who noted that the animation construction process itself played an important role in stimulating students to identify the entity "fog" and how this entity behaved to give rise to evaporation.

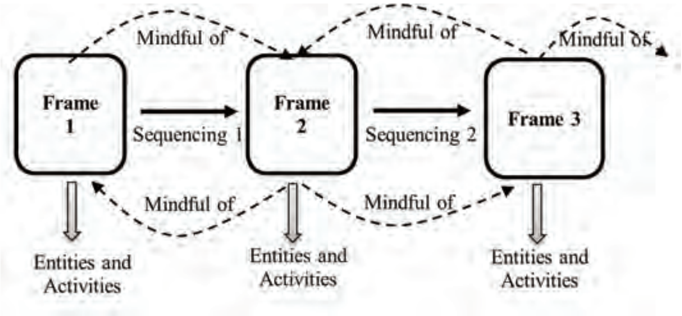


Figure 9. A way students build mechanistic reasoning through chunking and sequencing

Analysis of the data revealed that the construction of a stop-motion animation afforded opportunities for the students to engage deeply with content. This can be seen by the fact that the students' reasoning becomes more abstract in subsequent phases. In particular, Phase B elicited abstract reasoning most explicitly: there was a considerable increase in the number of abstract entities used. Moreover, even though most of the students did not start using those entities at the beginning (Phase A), they did so in Phase B. The notion that the trajectory will, at some point, have to flatten while the ball is in no way visibly connected to a changing agent is what appears to elicit the use of abstract entities. In this explanation, intangible concepts are needed, whereas the straight-line movement in Phase A does not require these concepts in principle, since nothing changes in the direction of the movement. The students thus introduce concepts, such as momentum, air resistance, and gravity, in phase B to explain the change in the direction.

The results of the analyses showed that the students who engaged in chaining were capable of gaining a deeper understanding of concepts. For example, Student B argued, using chaining, that for each position of the ball the motion was the resultant of two vector entities, i.e., gravity and momentum, so that the ball gradually moved down. On the other hand, Student A appeared to be unable to exhibit chaining in Phase C. She only argued that due to gravity pulling down, the ball moved down. However, she was not capable of explaining the reason why a pull by gravity prevented the ball from falling down in a straight line.

Student A's failure to reason with chaining was attributed to lack of either the presence of a property of entities (element 5) or an organization of these entities (element 6). Russ et al. (2008) argued that students who did not specify a relevant property of the entities seemed to use a scientific knowledge that they did not understand. Thus, if Student A used entities that made sense to her, we might expect that she could identify a relevant property of the entity. As a consequence, she might be then able to assign the specific activities of the entity that enabled the specific trajectory of the ball to happen or an increase in both speed and kinetic energy to occur.

6. Implication

The current study provides a first insight in how SMA can induce mechanistic reasoning, especially chaining and abstract reasoning in lower secondary students. In future studies this will need to be explored further, for instance how thinking about more aspects of mechanistic reasoning can be supported, such as set-up condition, properties of entities, and organization of entities. Additionally, we propose to conduct studies that focus on the differences in terms of elicited mechanistic reasoning between SMA on the one hand, and other forms of representation (e.g., simple drawing and thinking aloud about the drawings) on the other. Also the studies should extend to other domains (e.g. multi-agent systems) and student groups (e.g. from primary school to university). A quasi-experimental design to compare the quality of learning science through a stop-motion animation to the other modeling approaches would also be very useful (Farrokhnia et al., 2020). This comparison could also include expert-generated animations to investigate whether students' reasoning strategies for learning science with such models differ.

CHAPTER 4 Understanding how student-constructed stop-motion animations promote mechanistic reasoning: A theoretical framework and empirical evidence

This chapter is based on:

Bachtiar, R. W., Meulenbroeks, R. F. G., & van Joolingen, W. R. (2023). Understanding how student-constructed stop-motion animations promote mechanistic reasoning: A theoretical framework and empirical evidence. *Journal of Research in Science Teaching*. https://doi.org/10.1002/tea.21891

Abstract

Previous studies have documented the promising results from student-constructed representations, including stop-motion animation (SMA), in supporting mechanistic reasoning (MR), which is considered an essential thinking skill in science education. Our current study presents theoretically and empirically how student-constructed SMA contributes to promoting MR. As a theoretical perspective, we propose a framework hypothesizing the link between elements of MR and the construction nature of SMA, i.e., chunking and sequencing. We then examined the extent to which this framework was consistent with a multiple-case study in the domain of static electricity involving five secondary school students constructing and using their own SMA creation for reasoning. In addition, students' reasoning in pre- and post-construction of an SMA was examined. Our empirical findings confirmed our framework by showing that all students identified the basic elements of MR, i.e., entities and activities of entities, when engaging in chunking and sequencing. Chunking played a role in facilitating students to identify entities responsible for electrostatic phenomena, and sequencing seemed to elicit students to specify activities of these entities. The analysis of students' reasoning in pre- and post-construction of SMA found that student-generated SMA has a potential effect on students' retention of the use of MR. Implications for instruction with SMA construction to support MR are discussed.

Keywords

Mechanistic reasoning, stop-motion animation, slowmation, physics, cognitive tools

1. Introduction

One of the major goals of science education is to foster students' ability to provide scientific explanations for natural phenomena (National Research Council, 2012; NGSS Lead States, 2013). Braaten & Windschitl (2011) argue that this explanation type is intended to describe the causes of natural phenomena by involving unseen entities such as atoms, as exemplified in explaining that the behavior of gases requires the use of molecular kinetic theory. We posit that constructing this kind of explanation needs to use a type of thinking called mechanistic reasoning (MR), which specifies both entities and the actions these entities take. In addition to the benefits of MR to generate scientific explanations, a recent literature study shows the importance of MR in science education (Bachtiar et al., 2022), also highlighted by science education research (e.g., Balabanoff et al., 2020; Becker et al., 2016; Macrie-Shuck & Talanquer, 2020; Russ et al., 2008; Southard et al., 2016; Weinrich & Talanquer, 2016; Wilkerson et al., 2018). For example, students who used MR to explain a physical phenomenon demonstrated a higher level of conceptual understanding than students not using MR (Balabanoff et al., 2020; Cooper et al., 2016; Crandell et al., 2019).

Despite the value of MR in science education, researchers noted challenges of getting students to generate MR (see Bachtiar et al., 2022; Moreira et al., 2019; Southard et al., 2017; Talanquer, 2018; Zotos et al., 2021). The lack of domain-specific knowledge, such as proteins (van Mil et al., 2016), atomic structure (Balabanoff et al., 2020) contributed to students' failure to generate MR. A preference to use MR for reasoning about a target phenomenon was reported to be particularly difficult (Bachtiar et al., 2022). For instance, students tended to redescribe the target phenomenon (e.g., Dood et al., 2020; Talanquer, 2010). Also, students involved entity atomic particles, e.g., electrons, in the explanations of chemical reactions, but the interactions among the particles were not described, so that their reasoning was not classified as MR (Becker et al., 2016).

Given the fact that developing MR is notoriously challenging for students, several studies put forward proposals for supporting MR. For instance, Bolger et al. (2012) proposed a simple mechanical system of levers, which has visible components, as a tool that can be used by students to practice MR. Additionally, Weinberg and Sorensen-Weinberg (2022) supported students' MR about the systems of levers through engaging them in physically experiencing the components and forces within such mechanic systems. Tate et al. (2020) proposed the so-called Web-based Inquiry Science Environment as a technology-based explanation tool to help students use MR about biological phenomena. Also, Mathayas and colleagues (Mathayas et al., 2019, 2021) documented that gesturing with a computer simulation is helpful for students to develop MR.

Highlighted by our literature study (Bachtiar et al., 2022), also reported by other studies (e.g., Andrade et al., 2021; Bachtiar et al., 2021; Wilkerson-Jerde et al., 2015; Wilkerson et al., 2018), students used MR when reasoning with their own creation of a model of a phenomenon. Given a growing research interest in student-constructed stop-motion animations (SMA) as digital explanations that have been shown to support science learning (see Farrokhnia et al., 2020; Hoban, 2020; Nielsen et al., 2022; Paige et al., 2016; Yaseen & Aubusson, 2018), our present study focuses on exploring the contribution of student-constructed SMA for specifically supporting MR.

Previous studies have reported convincing evidence of student-constructed SMA for supporting MR (e.g., Bachtiar et al., 2021; Wilkerson-Jerde et al., 2015; Wilkerson et al., 2018). Wilkerson et al. (2018) found that when constructing a model of water molecules in evaporation phenomena using a computer modeling tool, i.e., SiMSAM, some fifth grade students were engaging in a particular way of thinking, called EM&I (i.e., "entities, movements, and interactions"), in which such thinking relates to MR. Wilkerson and colleagues made use of a theoretical perspective, i.e., epistemic forms (as model forms) and epistemic games (ways of thinking one engage during the construction of a model), to understand why the corresponded modeling tool elicited such way of thinking. The work by Wilkerson and colleague and their theoretical perspective calls for a follow-up question: "if so, in what ways". This question implies the need to provide a pragmatical perspective that could explore in depth how the nature of SMA construction, i.e., chunking and sequencing, could promote MR. To do so, we propose a theoretical framework depicting a connection between seven elements of MR proposed by Russ et al. (2008) and such construction nature of SMA. We then examine the extent to which the framework aligned with the findings from a multiple case study examining students constructing an SMA model of systems inherently requiring reasoning at microscopic scales, i.e., electrostatic phenomena. By aligning our framework to such empirical evidence, we expect to be able to obtain a comprehensive understanding of why and how engaging students in the construction of SMA contributes to promoting MR.

In this regard, we use the following research questions:

1. *To what extent do student-generated SMA contribute to students' MR in reasoning at microscopic levels?*
2. *What is a plausible mechanism for the promotion of elements of MR during the construction of SMA?*

The first research question is intended to look at how students reasoned about electrostatic phenomena before and after constructing an SMA. The second research questions are aimed to relate our hypothetical framework to the findings of experimental settings by identifying elements of MR that students employed when using their own SMA creation to explain electrostatic phenomena.

2. Theoretical background

2.1 Mechanistic reasoning

Our study draws on the framework of seven elements of MR proposed by Russ et al. (2008), developed from the work by Machamer et al. (2000) describing the concept of mechanisms. These seven elements were utilized to identify MR in students' thinking; these are as follows: (1) describing the target phenomenon, (2) identifying setup conditions, (3) identifying entities, (4) identifying activities of entities, (5) identifying properties of entities, (6) identifying organization of entities, (7) chaining, as the highest level of MR. For the full descriptions of each element, see Russ et al.'s work on page 512-513.

These elements were adapted from the components of mechanisms pointed by Machamer et al. (2000).

> "Mechanisms are sought to explain how a phenomenon comes about […] 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." (Machamer et al., 2000; p.1-2).

To specify the notion of entities and activities, Machamer et al. (2000) exemplified the mechanisms of neurotransmission, i.e., "a presynaptic neuron transmits a signal to a post-synaptic neuron by releasing neurotransmitter molecules that diffuse across the synaptic cleft, bind to receptors, and so depolarize the post-synaptic cell." (p.3). Neurotransmitter molecules and receptors refer to entities, while "bind" refer to activities.

Russ et al. (2008) defined entities as "the things that play roles in producing the phenomenon" while activities attend to "the various doings in which these entities engage" (p. 512). Russ and colleagues illustrated these elements with an example of students' discourse about a free-fall motion phenomenon, i.e., "gravity is pulling the book down". In this case, gravity is identified as an entity, and "pulling down" refers to the activities gravity engages.

Other literature on MR may use different terms to name entities and activities, but basically these refer to the same ideas. As shown by Bechtel and Abrahamsen's (2005) study, "[…] mechanistic explanation: A mechanism is a structure performing a function in virtue of its component parts, component operations, and their organization […]" (p. 423). "Component parts" relate to entities, and "component operations" attend to activities.

In relation to the topic in our current study, consider the following example. A teacher is demonstrating electrostatic phenomena: a balloon can stick to the wall after the balloon has been rubbed against someone's hair. The teacher then asks his students to provide an explanation of what was happening when the balloon was being rubbed against hair. Suppose Student 1 says that "when the balloon is being rubbed against hair, the balloon is getting energy." While Student 2 says that "when the balloon is being rubbed against hair, electrons from the hair move to the balloon. As a result, because the charge of an electron is negative, the balloon now becomes negatively charged".

To be called MR requires involving both elements of MR, i.e., entities and activities (Bachtiar et al., 2021). In addition, MR should involve entities at (at least) one scale level below the scale level of a target phenomenon, such as using molecules as entities to explain the changing state of matter. Entities may relate to abstract concepts, such as force, energy, or concrete ones, such as a ball, a car, a balloon, etc.

Based on the aforementioned, Student 2's reasoning is what we call MR because the explanations contain two basic elements of MR, i.e., entities (electrons) and activities (the movement of electrons). In contrast, Student 1's explanations are not classified as MR because even though Student 1 mentions energy and energy could be considered an entity, the student does not specify activities of the entity energy. In addition, in Student 2's explanation, properties of entities (negative charges) are also identified. Moreover, Student 2 reaches chaining by stating that the balloon becomes negatively charged.

2.2 The affordance of SMA as a modeling tool

Modeling tools within science education research can take many form, ranging from computer-based tools (see Louca & Zacharia, 2008; Pierson et al., 2020; Sengupta & Wilensky, 2011; van Joolingen and de Jong, 2003), to relatively low-tech tools, e.g., paper-based drawings (e.g., Ainsworth et al., 2011; Tang et al., 2019; Tytler et al., 2020). The actual choice in a given situation depends on different factors, e.g., the level of dynamics required (Chang et al., 2014; Louca et al., 2011), or the target age groups (Chang et al., 2010; van Joolingen et al., 2015). For example, computer-programming tools, such as NetLogo (Sengupta & Wilensky, 2011), Stagecast creator (Louca et al., 2011), StarLogo Nova (Pierson et al., 2020), and Simquest (van Joolingen & de Jong, 2003), can be used to model highly dynamic processes. Using these computer tools usually requires knowledge of programming codes or mathematical formalisms, making them less evident for use by younger students or novice modelers (Sins et al., 2005). Young children could benefit from paper-based drawings, but drawing-based models are less appropriate to visualize a dynamic process.

Our study involves SMA as a modeling tool. As commonly known, an SMA is formed by taking several digital still photographs (called frames), and sequencing them in a time-ordered fashion. Constructing an SMA model does not require explicit modeling rules. Students just need to take a series of static pictures using ubiquitous SMA software. Freeware SMA applications are widely available and can be run on many devices, e.g., computers, tables, or smartphones. Thus, modeling using SMA is accessible to young children (e.g., Brown et al., 2013; Fridberg & Redfors, 2018), but also to more mature students, e.g., preservice teachers (e.g., Nielsen & Hoban, 2015).

SMA shares similarities with a common animation-based modeling tool in terms of the intended learning goals. Either SMA or an animation can be used to support teaching and learning about dynamic contents, e.g., motion. Students-constructed SMAs have been shown to be beneficial to teaching and learning about, e.g., chemical processes at sub-microscopic levels (Berg et al., 2019), plate tectonics (Mills et al., 2019), evolutions (Orraryd & Tibell, 2021), phases of the moon (Nielsen & Hoban, 2015), and parabolic motion (Bachtiar et al., 2021). Likewise, allowing students to create an animation could promote their understandings about dynamic aspects of chemical reactions (Chang et al., 2014).

SMA, in the other hands, differs from an animation in the *substance* of presentation. The inherent step-by-step approach of SMA has its specific advantages in education. Consider the case of motion, a continuous animation shows the motion *as a whole*, whereas SMA illustrates a series of different stages of this motion. Höffler et al. (2013) point out that a series of static pictures, as the basic presentation of SMA, might be more appropriate when aimed at understanding essential steps in certain dynamic processes. Exemplified in the biological phenomena, i.e., the mitosis or meiosis processes of cell division, the transitions from the prophase to the metaphase to the anaphase and so on are clearly identified by visualizing a series of static pictures. Bachtiar et al. (2021) found that students were stimulated to think deeply about abstract concepts, e.g., gravity, energy, when tasked to create and reason about an SMA model of the ball motion in parabolic trajectory showing a series of one particular positions of the ball.

2.3 The fundamental principle of SMA construction

We draw on the concept of cognitive tool (Jonassen, 1992; Kim, 2012; van Joolingen, 1999) to argue that SMA as a modeling tool could be serve as a cognitive tool. Jonassen (1992) defined cognitive tools as "external, computer-based devices and environment that extend the thinking processes of learner" (p.1). Kim (2012) examined the different views of cognitive tools formulated by different researchers and found a consensus on the definition and the role of cognitive tools in learning: (1) "knowledge is actively constructed by students, not transmitted from teachers; and (2) tools, computers, and artifacts can play an important role in the dynamic processes of knowledge-building". van Joolingen (1999) revealed that any tools, even a paper sheet and a pencil, could serve as cognitive tools when these tools "can impose a structure on a reasoning process" (p.389). Drawing upon this perspective, we argue that the construction of SMA can be considered a cognitive tool that supports and direct a particular cognitive process.

Hoban and colleagues describe that the process of constructing an SMA (called "slowmation" in these sources) involves five stages resulting in five different products, i.e., (1) research notes, (2) storyboards, (3) models, (4) digital still photos, and (5) the narrated animation (Hoban et al., 2011; Hoban & Nielsen, 2010, 2013). Stage 1 (research notes) is basically intended for students to gather information so that they gain "enough background knowledge before designing an animation […] Alternatively, a teacher may specifically teach students the basics of a particular concept" (Hoban & Nielsen, 2010; p.37). In our view, students could also rely on their prior knowledge as a starting point for creating an SMA. In stage 2, students create a storyboard through "chunking and sequencing" (Hoban et al., 2011; p.996). We argue that both chunking and sequencing are fundamental principles in the construction of an SMA, and involve associated cognitive processes. Chunking refers to a process "to break a target concept down into its constituent elements or ''chunks''," while sequencing attends to a process whereby "each chunk then needs to be placed in a sequence to bring the anticipated actions and explanations into a coherent order" (Hoban et al., 2011, p.996). While Hoban and colleagues point to the fact that the last four stages (i.e., stage 2 to stage 5) result in different products, we argue that to produce these products, all of these stages rely on the cognitive processes related to chunking and sequencing. Hoban and Nielsen (2010) state that stage 3 involves "the students thinking about the chunks of the concept in concrete ways and the best way to represent the concepts is in a sequence […]" (p.37). We argue that students could engage in these four stages simultaneously, supported by the claim by Hoban and colleagues that the process of constructing representations in these stages is not linear, but rather iterative (Hoban et al., 2011; Hoban, 2020). Therefore, our study focuses on chunking and sequencing as the nature of SMA construction and the underlying cognitive processes.

Creating an SMA implies constructing a sequence of chunks. We argue that the construction of these chunks elicits particular cognitive processes. Gravel (2009) points out that an SMA (dubbed "SAM animation" in this publication) is built from a series of frames, in which "each frame could be conceived of as an instance in time - representing one particular moment", which implies forcing "students to think in time" and "recognizing what, exactly, is changing" over time (Gravel, 2009; p.4). Each chunk ("frame" in this quote) represents one particular moment, or state of a target phenomenon. Questions such as "what is exactly changing" from one chunk to the next, characterize the cognitive process related to the construction of the sequence of chunks.

Visualizing chunks in concrete ways and sequencing the chunks in a coherent order has the potential to support MR. In an SMA chunks take the form of photos, e.g., of 3D materials, such as Play-dough clay. These chunks, basically snap shots of a state within a phenomenon can be considered to be similar to a drawing in drawings-based modeling. Studies have shown that expressing concepts, situations, and phenomena in a drawing can be employed to promote model-based reasoning and support students in reasoning about mechanisms, e.g., involving the structure and behavior of molecular-level entities (see Andrade et al., 2021; Cooper et al., 2017).

However, sequencing chunks, an essential element of SMA, requires thinking about the transition between chunks and thus necessarily involves the dynamic nature of the phenomenon under discussion. Thinking about the transition from one chunk to the next involves addressing particular questions about "why and how the change happens". Studies have shown that "how and why" questions led students to construct mechanistic explanations (e.g., Cooper et al., 2016; Crandell et al., 2019), implying the use of MR to construct such explanations. Thus, the explicit inclusion of the time factor in SMA forces students to consider the time-dependence of phenomena, an aspect that is more difficult to visualize in drawing-based modeling.

We conjecture that modeling on the basis of chunking and sequencing (thus creating an SMA) elicits a specific cognitive process that is needed to address the associated questions. Such cognitive processes involve MR. In the following section, we propose a theoretical framework illustrating how the construction of SMA, as modeling and a cognitive tool, promotes elements of MR.

2.4 A framework linking between the construction nature of SMA and elements of MR

Drawing upon the perspective aforementioned, we hypothesize that MR is involved when constructing the chunks and sequencing them, i.e., thinking about the transitions between them. Figure 1 presents our framework conveying how the construction nature of SMA works in promoting elements of MR.

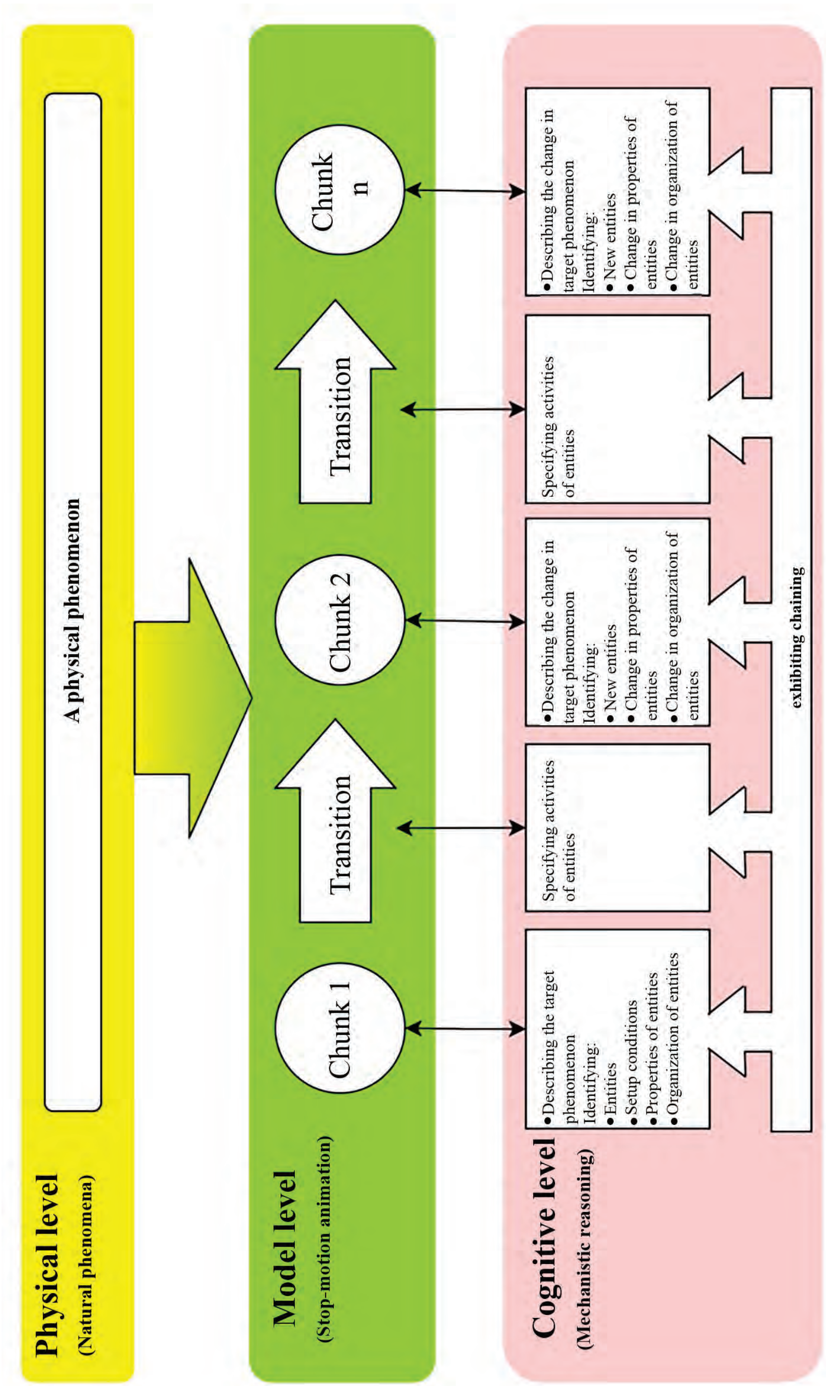


Figure 1. A theoretical framework for cognitive processes in SMA construction.

Our framework illustrates the interconnection of three levels, i.e., Physical, Model, and Cognitive levels. Physical level refers to natural phenomena that are targeted to be modeled; in our study, the target phenomenon attends to static electricity. Model level concerns a model form of SMA as a representation of a target phenomenon. Cognitive level relates to elements of MR connected with the SMA model.

At the Physical level, students consider content to be a representation of a target phenomenon. For example, to present electrostatic phenomena generated by a balloon being rubbed in the hair, a student should consider the movement of electrons from the hair to the balloon. At the Model level, students translate this content into an SMA model by chunking and sequencing. Students need to create n chunks and sequence these chunks in a coherent order.

In relation to the Cognitive level, when students construct Chunk 1, as illustrated in our framework, they are thinking about a state of a target phenomenon by describing the target phenomenon, and identifying entities, setup conditions, properties of entities, and organization of entities. For example, as in the case of the electrostatic phenomena, the student creates Chunk 1 to represent a state of the balloon at the microscopic level at the moment before the balloon is rubbed. When representing this state, the student is thinking about equal numbers of electrons and protons on the balloon and the hair. By doing so, the student is describing the target phenomenon and identifying entities.

Then, when thinking about the transition between Chunk 1 and the next chunk, students are required to specify activities of entities; otherwise nothing would change in the next chunk. In the case of the electrostatic phenomena, the student needs to specify an action entities take, such as electrons moving from the hair to the balloon.

When constructing Chunk 2, students describe the change in the target phenomenon and identify new entities, change in properties of entities, and change in organization of entities. For the electrostatic phenomena, Chunk 2 could represent a new state of the balloon at the microscopic level. When representing this state, the student may reason that the balloon gets extra electrons so that the number of electrons and protons is no longer equal. By doing so, the student is describing the change in the target phenomenon along with identifying new entities in the sense of an additional number of electrons.

Finally, when thinking about the whole sequence of chunks, students exhibit chaining. In the case of the electrostatic phenomena, the student might reason that because three new electrons move from the hair to the balloon, the number of electrons is more than that of protons, so the balloon now becomes negatively charged.

3. Methods

3.1 Research method and participants

Apart from a theoretical perspective, the main goal of our current study is to understand empirically how the construction of SMA works in promoting MR. To reach this goal, we employed a multiple-case study (Gustafsson, 2017; Stake, 2013; Yin, 2013). This research design is appropriate when (1) research questions mainly focus on "how" and "why" questions leading to the need for typical data research, e.g., learning process (rather than outcomes), to address such questions, (2) researchers have less control in manipulating behavior directly, precisely, and systematically, and (3) research aims are to investigate "a contemporary phenomenon (the "case") in depth and within its real-world context" (Yin, 2013). Despite a limitation on generalization, conclusions generated from case studies could "shed empirical light about some theoretical concepts or principles […] to be applied in reinterpreting the results of existing studies […] or to define new research" (Yin, 2013).

Our cases refer to individual students creating an SMA model of an electrostatic phenomenon and using this SMA model to explain the reason for the phenomenon. Our multiple-case study involved five students (1 male and 4 females; ages 16-18) from two different secondary schools in the center of the Netherlands. They all had acquired some prior knowledge about static electricity at school. None of them had previous experience with the computer modeling tool employed in this study, i.e., HP Sprout. Three of them had experience in creating an SMA using another SMA software. During the study, we introduced the computer and asked all students to practice making an SMA using this specific computer before embarking on the main task. We conduct a rigorous cross-case analysis to find out commonalities and differences among student cases to explore how the construction nature of SMA promotes students' MR.

3.2 Research procedure and data collection

We collaborated with secondary-school science teachers to recruit students as research participants. In the research invitation letter, we explained the research, such as the study procedure, the location of the study, subject, a consent letter to be signed by parents, voluntary research participation. Participation in this study was voluntary. The study took place after school in the research facility of the researchers' university. Once the students responded to this invitation, we scheduled and invited each student to come to the research facility.

The study was conducted through tasks-based one-on-one interviews. The first author served as an interviewer. Before carrying out the interviews, we asked whether the students had been informed of the research procedure sufficiently. When the students did not require further information and had no questions, they were then asked to give their research consent. Then, the students followed four parts of the interview such as the following (a pilot interview had been also carried out by the first author and then all research members discussed the notes from this pilot interview until reaching the desired interview procedure; this pilot interview was used to establish the interview protocol and timing):

1. Part 1: Pre-discussion on Video 1
2. In this segment, the interviewer played back Video 1 presenting an electrostatics phenomenon. That is, a man is rubbing a balloon against his hair. Then, when he brings the balloon toward little pieces of paper, some jump to the balloon. After

watching the video, the interviewer asked question to the students : “why this phenomenon could happen?”. Additionally, the interviewer asked follow-up questions of any concepts the students mentioned. For example, “you just said the balloon has energy, what do you mean by energy?”

3. Part 2: Creating SMA
4. In this segments, the students created an SMA using the built-in SMA software on a HP Sprout computer. They were introduced to the basic features of SMA software. Also, they were asked to practice creating a simple SMA: a car moves from one position to another position. Once they were familiar with the software, they could start creating their main SMA.
5. The task of creating the main SMA was to construct an SMA based on the ideas they generated in Segment 1. The students were provided the material for creating the SMA, i.e., two types of Play-dough clay (yellow and pink), little pieces of paper, a puppet and a balloon. During the construction process, the students were welcome to change or add to the ideas if needed. The interviewer did not intervene and only provided technical help.
6. Part 3: Narration on the SMA creation
7. In this segment, the students were asked to explain their own SMA creation. When the students mentioned any science concepts during explanations, even if these were not new, the interviewer used follow-up questions, just like in Segment 1. Also, the interviewer asked for clarification. For example, “why the paper starts to move when the balloon is close enough, not from the beginning of the balloon’s movement” or “why do only three pieces of paper jump to the balloon, while the rest stays here.”
8. Part 4: Post-discussion on Video 1 and discussion on Video 2
9. In this segment, the students re-watched Video 1 and were tasked to respond to the interviewer’s questions: i.e., “why does the phenomenon displayed in this video happen?”. The students then watched the second video displaying another electrostatics phenomenon, i.e., a man first tries attaching the balloon to the wall, but it does not stick. He then rubs the balloon against his hair, and then re-attaches it to the wall. The balloon now sticks to the wall. The interviewer then asked questions “why does the phenomenon in Video 2 happen?. The interviewer asked follow-up questions of any science concepts the students mentioned. The interviews took about 60 minutes. Two video cameras were placed so that the students’ activities using the computer were recorded properly. To obtain a good audio quality data, a wireless microphone was attached to both the students and the interviewer. Also, Camtasia software was used to record on-screen activities. This case study research procedure fully complies with the ethical review for research procedure by the ethical review board of the university.

3.3 Data analysis

The analysis was conducted for the videotaped three parts of the interview (i.e., Part 1, 3 and 4) and the student-produced SMAs. The data analysis was conducted in three steps. First, the recordings were transcribed verbatim. Particularly, to complete the transcription, each student's utterances in Part 3 were related to the actual SMA. For example, when a student is saying "the next frames", it was indicated in the transcript that the student was using her/his hand to point at the last three frames.

Each student's utterances in each part were then coded using the seven elements of MR proposed by Russ et al. (2008). Additionally, the abstraction level of science concepts the students mentioned (i.e., whether these concepts were considered concrete concepts or abstract concepts) was coded. Table 1 is the coding scheme and the example of coded utterances. In addition, if a concept was mentioned more than once, this repetition was not coded. For example, if a student said, "There is [are] eight electrons, and six protons", two entities (element 3) with concrete concepts were identified in this utterance, i.e., electrons and protons. In the next utterances, the student stated "because of rubbing, the one electron moves towards", "electron" was not coded as an entity (element 3). We also involved a second coder to validate this coding process. About 20% of the coded utterances was checked. Interrater reliability analysis (Cohen's kappa) resulted in 0.758, indicating near-strong agreement (McHugh, 2012).

The second step of analysis was dedicated to addressing the first research question. The analysis was concerned with the coded utterances referring to the interview segments of Part 1 and Part 4. The results were presented in a scatter diagram plotting each element of MR mentioned by each student; see Figure 2 as an example. The results in the analysis of Part 1 and Part 4 were assigned to students' reasoning referring to the moment before constructing (called pre-construction of SMA) and after constructing an SMA (called post-construction of SMA), respectively. We then qualitatively compared the elements of MR used by the students before and after constructing an SMA.

Table 1. Coding scheme of mechanistic reasoning (adapted from Russ et al. (2008)) and the example of the coded utterances.

Elements of mechanistic reasoning	Example of students' excerpts
Element 1 (E1): Target Phenomenon. Students' utterances exhibit this element when students describe a target phenomenon without explaining mechanisms at the microscopic levels of how and why this phenomenon occurs.	Concrete: "when it [the balloon] comes close [to the paper; point to Frame 41], it's above, hmm, the pile is changing in form, some paper, part paper is attracted to the balloon" Abstract: "The more she rubbed it [the balloon], the more pink Play-Doh particles starts to appear [Point to Frame 18 to 24]"

Elements of mechanistic reasoning	**Example of students' excerpts**
Element 2 (E2): Setup Condition Students' utterances are classified as this element when students describe an initial condition that must occur before a target phenomenon happens.	Concrete: "because *the balloon wasn't rubbed long enough on your head*, it [the balloon] will not have the same charge for all of the paper" The italicized utterance is coded as E2 concrete, because this statement specifies the condition in the beginning before an attraction can occur. Abstract: "the paper was already positive to begin with. Because *that's six plus and four minus*, so it's too positive" The italicized utterance is coded as E2 abstract, because this statement specifies the initial condition for the balloon to become positively charged, thus resulting in an attraction.
Element 3 (E3): Entity An entity is an agent that plays a role in producing a target phenomenon. We code for the presence of this element in students' utterances when students try to identify the agents that cause a target phenomenon to happen. Those agents that are tangible are classified as concrete concepts, while abstract agents are theoretical	Concrete entity: electrons, protons Abstract entity: Energy
Element 4 (E4): Activity of entity An activity is what entities engage in order to produce a target phenomenon. We code students' statements as this element when students identify what entities do to give rise to a target phenomenon.	Concrete activity: "the one electron *moves* towards…" "there is an electron *going to* [points to the balloon]" Activity is "move" or "going to", and an entity is "electron" Abstract activity: "then here [frame 5] you can see that the energy *has been exchanged*" Entity is energy, Activity is "exchange"

Elements of mechanistic reasoning	**Example of students' excerpts**
Element 5 (E5): Property of entity An entity has particular characteristics (property). By having this property, the entity could do a specific activity. We code student's statements as this element when students identify the characteristics of an entity that are necessary for a certain activity.	Concrete property: "that could attract more yellow [papers], if there are *hundred pink* [point to Frame 9 and the balloon with pink clay], then it could attract *more yellow*" The number of little pieces of clay is considered to be a property of paper or balloon in order for an activity "attraction" to happen. Abstract property: "the paper goes off, because of, this is *positive* [points to the paper] and this is *negative*" "negative" or "positive" refers to property of electrons and protons, respectively, in order for an activity "attraction" to happen.
Element 6 (E6): Organization of entity and activity For a phenomenon to happen, a specific condition is sometimes required, e.g., where entities are located.	Concrete: "I think, it was still too far away […]The distance can't be too much" Abstract "the opposite charges from the paper is closer, then it will be attracted more, because *the force is bigger*"
Element 7 (E7): Chaining We code students' statements as chaining when students' explanations present a cause-effect relationship. This relationship signifies a claim about what *must have happened previously* to bring about the current state of things (backward-chaining) or what *will happen next* given that certain entities and activities are present (forward-chaining). In our study, all students' chaining is classified as forward-chaining. Also, when students construct a chaining, they involve not only *Entities* (E3) and *Activities* (E4), but also other elements of mechanistic reasoning. For example, a chaining consists of *Entities*, *Activities*, and a *Setup condition*. Because the students employ forward-chaining, their statements referring to the *next condition* are used to determine whether chaining is classified as concrete or abstract concepts.	Concrete: "how big the charges of the balloon, like if it [the balloon] is bigger, *it would attract more pieces of paper* with the account of charges" Abstract: "this one [points to the balloon] is just neutral […] because of the rubbing, the one electron moves […]. *Now [..] this one [the balloon] is negatively charged*."

The third step of analysis, with the aim of seeking to address the second research question and as the analysis of student cases, focused on each student-produced SMAs and students' reasoning with the use of their own SMA creation. Additionally, our framework served as an approach to identify the extent to which the framework was consistent with empirical evidence. To do so, the analysis started with finding out the characteristics of each SMA along with looking at the transcriptions for a detailed insight into SMA creation. This was accomplished through examining how electrostatic phenomena was represented in SMA. The SMA all shared a similar two-part structure, labelled Phase A and Phase B; these phases are described in detail in the results section. We then examined each student reasoning about these phases in terms of the elements of MR by looking at the coded student's utterances in Part 3 corresponding to these phases. The results of the identification of elements of MR were presented in a scatter diagram (see Figure 4 as an example).

We then conducted a fine-grained analysis of each student's SMA to identify: (1)how each phase was represented in SMA in the form of sequential chunks, and (2) students' explanations corresponding to one chunk, the following chunks and the transition between the chunks. To do so, we looked at the transcriptions and the actual SMAs to find out students' explanations referring to each frame that made up an SMA. To accomplish the analysis, we determined how frames could be considered a chunk and to distinguish between one chunk and the one following it. While one chunk depicts a state of a target phenomenon, the next one represents a new state of the target phenomenon. In our analysis, sometimes one chunk may consist of more than one frame. For example, a student argued that the first three frames illustrated an uncharged balloon (Chunk 1) and the next two frames depicted the charged balloon (Chunk 2), and then used the transition from chunk 1 to chunk 2 to argue that electrons were going from the hair to the balloon (sequencing the two chunks).

Based on the identification of each student's reasoning about one chunk, the next chunks and the transitions between chunks, we then examined the elements of MR that were exhibited in each reasoning, by looking at the coded students' utterances in Part 3. We then examined commonalities and differences among the student cases, then selected representative students to provide and illustrate in depth exploration of how chunking and sequencing promote elements of MR.

Throughout the analysis process, the findings were discussed among all authors. The discussion on the findings relating to the first step of analysis led to the consensus on the unit of analysis of entities: (1) only scientific concepts relating to static electricity were considered entities, (2) abstract entities refer to abstract concepts, such as energy, force, (3) concrete entities refer to tangible matter, such as electrons, protons. We consider electrons to be concrete matter because these are inherently particles even though they are invisible to the naked eye. Also, the discussion on the findings in this third analysis resulted in a new unit of analysis, i.e., clarification questions proposed by the interviewer (see the interview step 3) which was considered to be guiding questions. This new unit of analysis stemmed from the analysis of the conversation between the students and the interviewer, in which the interviewer needed to ask these clarifications questions of four students (Student 2, 3, 4 and 5) in order to get a complete idea of their SMA creation, but these questions were not necessary for Student 1.

4. Results

We begin with the results from analyzing the students' elements of MR in before and after constructing an SMA, followed by a summary of the characteristics of SMAs creation, along with presenting the elements of MR used by the students when reasoning with their own SMA creation. We then provide two students cases to illustrate in depth exploration of the contribution of chunking and sequencing to promoting the elements of MR.

4.1 Students' reasoning about electrostatic phenomena in pre- and post-construction of SMA

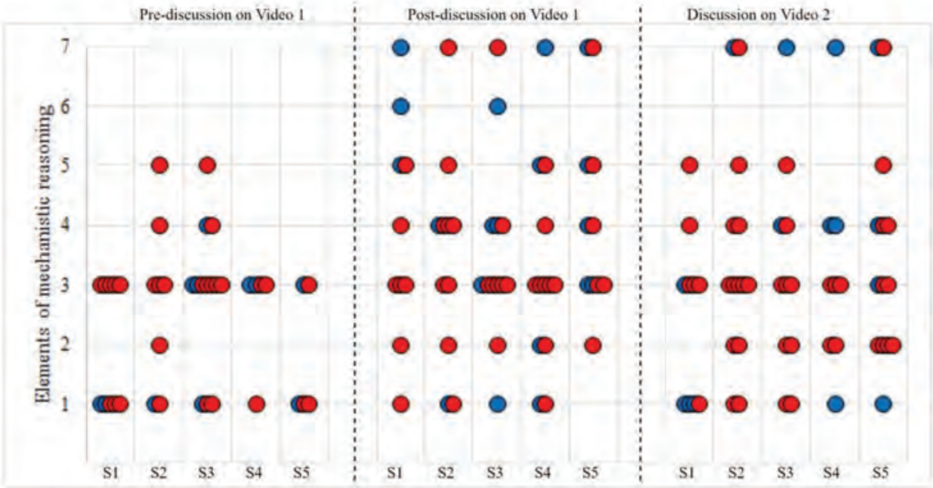


Figure 2. Elements of MR (on the vertical axis) used by each student (on the horizontal axis) to reason about electrostatic phenomena before (Pre-discussion on Video 1) and after (Post-discussion on Video 1 and Discussion on Video 2) constructing SMA. S1 = Student 1; S2 = Student 2; S3 = Student 3; S4 = Student 4; S5 = Student 5. Aside from the designation of elements of MR, a scatter plot signifies either concrete (blue circle) or abstract (red circle) concepts.

Figure 2 shows a scatter diagram resulting from the analysis of students' reasoning about electrostatic phenomena in pre- (pre-discussion on Video 1) and post- (post-discussion on Video 1 and Discussion Video 2) construction of SMA. This diagram plots each element of MR together with concrete (blue circle) and abstract (red circle) concepts used by the associated student. Additionally, the diagram could provide insight into the combined elements of MR from all students' reasoning.

In general, it can be seen that the construction of SMA appears to contribute to promoting MR. More elements of MR were involved in post-construction of SMA than before constructing SMA. For example, activities of entities (element 4), properties of entities (element 5) and chaining (element 7) appeared more often in post-construction of SMA. Regarding the findings of the analysis of the abstractions level of concepts, we did not see any patterns of the students' explanations.

Looking at individual students, as shown in the diagram, three students (Student 1, 4 and 5) did not exhibit MR before constructing an SMA. When explaining the phenomenon displayed in Video 1, these three students only identified entities responsible to the phenomenon without specifying activities of these entities. However, all five students exhibited MR (i.e., used at least entities and activities of entities) after creating an SMA. Moreover, these five students all demonstrated chaining, as the highest level of MR, when re-explaining the phenomenon displayed in Video 1. Even though not all students reach chaining when explaining the phenomenon displayed in Video 2, the reasoning generated by all students can be classified as MR.

4.2 The use of SMA creation to reason about electrostatic phenomena

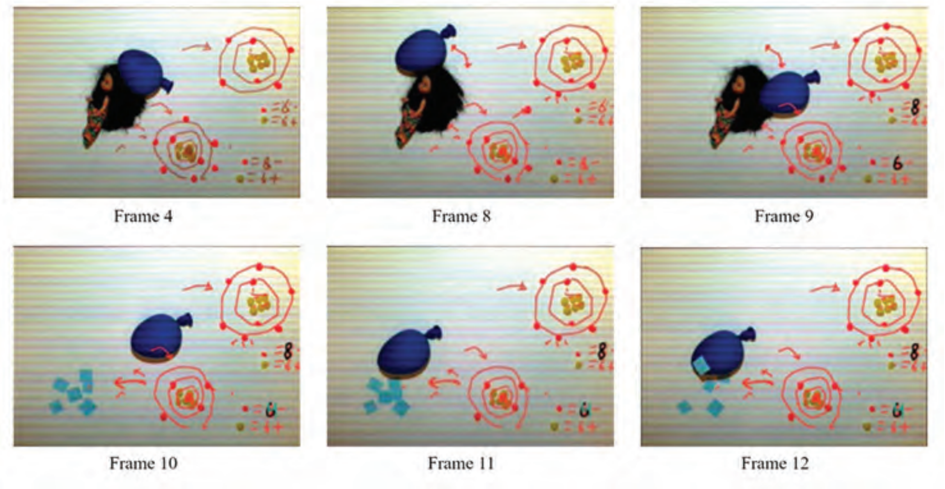


Figure 3. An example of frames from the animation created by Student 5; see Supplementary Animation S1 for the full frames and the animation.

This section presents the findings on: (1) the characteristics of SMA created by each student, and (2) each student's use of MR during explaining his/her SMA creation on the basis of the recorded narrative. All five students constructed an SMA depicting two demonstrations of electrostatic phenomena, i.e., Phase A and Phase B; Figure 3 presents an example of the frames from the animation created by a student (see Supplementary Animation S1 for the animation). Additionally, all students depicted each phase in an SMA model in the form of two sequential chunks.

The two sequential chunks referring to Phase A illustrated the change in the state of the balloon at the microscopic level. That is, an electrically neutral balloon became a charged balloon when the balloon was being rubbed against someone's hair. In Phase B, the two sequential chunks depicted states of the microscopic particles on the balloon and on the little pieces of paper at the moment when the balloon was being moved toward the paper.

Figure 4 presents a scatter diagram plotting the elements of MR used by the associated student when explaining his/her own SMA creation. The diagram contains three scatter plots. First, “Phase A” and “Phase B” refers to students’ reasoning about Phase A and Phase B, respectively. “Phase B + guiding questions” concerns students’ reasoning about Phase B with addition of guiding questions, i.e., clarification questions from the interviewer. Note that, as mentioned in the method section, guiding questions were only used with Student 2, 3, 4, and 5.

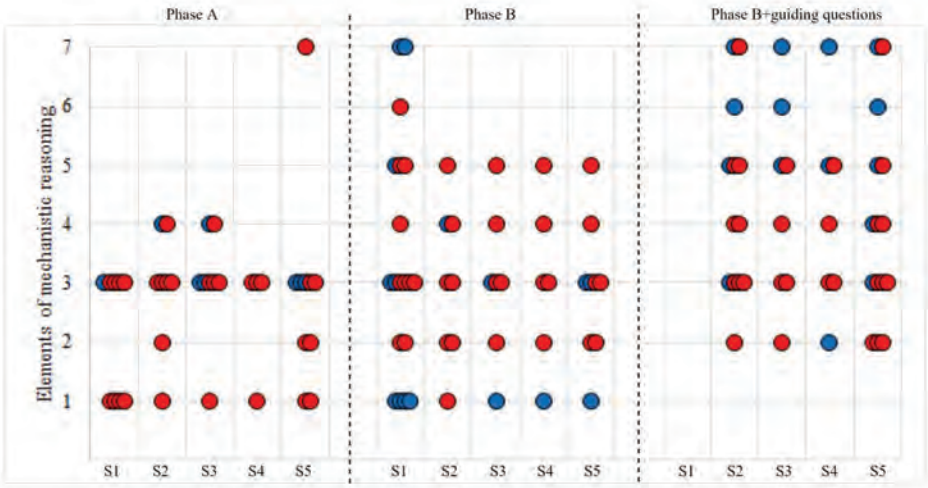


Figure 4. Elements of MR (on the vertical axis) used by each student (on the horizontal axis) to reason about electrostatic phenomena when using their own SMA creation. S1 = Student 1; S2 = Student 2; S3 = Student 3; S4 = Student 4; S5 = Student 5. Aside from the designation of elements of MR, a scatter plot signifies either concrete (blue circle) or abstract (red circle) concepts.

Based on the results of Phase A, we classified the students into two groups. Group 1 is composed of two students, i.e., Student 1 and 4, who did not use MR when reasoning about Phase A. Group 2 consists of three students, i.e., Student 2, 3, and 5, who used MR to reason about Phase A. Notwithstanding the differences in Phase A, all five students exhibited MR when reasoning about Phase B. Additionally, Student 1 even spontaneously demonstrated chaining in Phase B, and the rest of the students could do so after a question prompt was provided.

4.3 Case studies

Based on the findings identified in Figure 4, in this section, we provide two representative student cases, i.e., Student 5 and 1, to illustrate in detail and to substantiate the claim that engaging in chunking and sequencing encourages students to identify elements of MR. Student 5 exhibited MR when reasoning about Phase A and B. Student 1 started demonstrating MR when reasoning about Phase B. Also, Student 5 reached chaining after providing guiding questions, whereas such questions were not necessary for Student 1 to reach chaining.

4.3.1 The case from Student 5: SMA supports MR in both Phase A and B

Table 2 contains the utterances of Student 5 who was explaining Phase A using her own SMA creation. She created Frame 1 to 9 (see the example of frames in Figure 3) to represent an SMA model of Phase A in the form of two sequential chunks. The first chunk depicted a state of the balloon at the microscopic level at the moment before the balloon was rubbed against the hair, i.e., an electrically neutral balloon meaning that the number of protons and electrons is equal (see Frame 4). The second chunk illustrated the new state of the balloon at the microscopic level, i.e., the electrically charged balloon representing that there is no equal number of protons and electrons in the balloon (see Frame 9).

Table 2. Student 5's utterances referring to Phase A

Line	Utterances	
32	S:	This is just introduction to the hair and to the balloon [points to Frame 1]. And here, this [points to Frame 2 and 3] is used, so I can introduce that this is an electron [a piece of pink clay] and this is a proton [a piece of yellow clay].
33	S:	And here [points to Frame 4] I have the atomic level of the hair, molecules, I guess, I don't know, hmm, atoms. There is eight electrons, and six protons [points to the hair], so it [the hair] has a negative, hmm, lading [Dutch: charge], a negative hmm, I don't know the word in English, I think like, well, it [the hair]is negative like if you six minus eight, is minus two. So it [the hair] has a negative, yeah I don't know the word. And this one [points to the balloon] is just neutral, I guess, for the balloon
43	S:	now, its, this frame [points to Frame 4] is to get the balloon to the hair. And to show that it's gonna, that it's rubbing against the hair [points to Frame 5 and 6]
44	S:	And then you can see that [points to Frame 7], because of the rubbing, the one electron moves towards, hmm, the atoms from [of] the balloon, hmm, yeah maybe this should have been, um have a positive charge, I don't yeah, charge, I guess, but yeah, I don't know, I didn't do that. So now [points to Frame 8] there is an electron going to [points to the balloon], the atoms from [of] the balloon, as you can see two of them [pointing to two pieces of yellow clay, as electrons, that moves to the balloon from the hair]
45	S:	Now [Frame 9], this one [point to the balloon] is, hmm, this one [the balloon] is negatively charged and this one [the hair] is neutral. But yeah the hair doesn't really matter anymore after this.

When describing the first chunk, in line with our framework, the student described the target phenomenon, i.e., the state of the balloon at the microscopic level before the balloon was rubbed against the hair, together with identifying four entities, i.e., electrons, protons, molecules, and atoms (see line 33 and 34). In addition, two setup conditions relating to either the balloon or the hair were identified, as shown by her statements in line 33 that "there is eight electrons, and six protons [points to the hair], so it [the hair] has a negative […] this one [points to the balloon] is just neutral". However, the student did not identify either the properties of entities or the organization of entities.

When illustrating the transition between Chunk 1 and Chunk 2, the student specified activities of entities “electrons”, i.e., electrons are moving. As illustrated in line 44, she stated that “you can see that [points to Frame 7] […] there is an electron going to” the balloon from the hair. Thus, due to the movement of these electrons, it led to the new state of the balloon at the microscopic level, as represented in the second chunk.

When describing the second chunk, the student described the change in the target phenomenon, that is the new state of the balloon at the microscopic level. Along with describing this state, the student also identified two new unseen entities, in the sense of there being two electrons moving to the balloon. As the student mentioned in line 44, “so now [points to Frame 8] there is an electron going to [points to the balloon] […] as you can see two of them [pointing to two pieces of yellow clay, as electrons, that moves to the balloon from the hair]”. The student did not identify either the change in the properties of entities or the change in organization of entities.

When describing these two sequential chunks, the student demonstrated chaining. The student could reveal that there was the new state of the balloon due to the additional number of electrons. As mentioned, “this one [points to the balloon] is just neutral” (line 33) initially. She then argued that when the balloon was being rubbed against the hair, “there is an electron going to” (line 44) the balloon from the hair. As a result, the balloon “is negatively charged” (line 45).

Table 3. Student 5’s utterances referring to Phase B

Line	Utterances	
58	S:	This [points to Frame 9] was still to show that now all electrons are here [point to the balloon], and you can see that this one [the balloon] is negative and this one [the hair] is neutral
59	S:	So now [points to Frame 10], you can see the paper, and the paper was already positive to begin with. Because that’s six plus and four minus, so it’s too positive.
61	S:	[…] And then you have the balloon [Frame 10], it [the balloon] has eight electrons and six proton, so it’s, hmm, negative
62	S:	And because of negative, the positive attracts negative and the other way around. Because of that, in the next frames [points to Frame 11 and 12], the paper goes off, because of, this is positive [points to the paper] and this is negative [points to the balloon], yeah, that’s just how it work
70	S:	[…]hmm, the paper has a positive charge and the balloon has a negative charge so then the atoms in the paper are attracted to the atoms in the balloon, and then they [the little pieces of paper] move toward [the balloon]

Table 3 contains Student 5’s utterances referring to Phase B. The student constructed an SMA, particularly Frame 10 to 12 (see Figure 3), to represent Phase B in the form of two sequential chunks. The first chunk demonstrates a state of the balloon and the little pieces of paper at the microscopic level. When describing the first chunk (see line 58, 59, and 61), in accordance with our framework, the student identified unseen entities, i.e., electrons and protons (see line 58, 59 and 61), along with identifying properties of these entities, i.e., positive refers to protons and negative refers to electrons, and identifying the setup conditions representing the condition of either the balloon or the paper enabling an attraction among unseen particles to occur. As mentioned, “This [points to Frame 9] … now all electrons are here [points to the balloon]” (line 58), so that the balloon is “negative” (line 58) because “it [the balloon] has eight electrons and six proton” (line 61), while the paper “was already positive. Because that’s six plus and four minus” (line 59).

When illustrating the transition between Chunk 1 and Chunk 2, the student specified activities of entities. She argued that there were interactions among unseen entities, as seen in line 62, i.e., “And because of negative, the positive attracts negative and the other way around”, and line 70, i.e., “, the paper has a positive charge and the balloon has a negative charge so then the atoms in the paper are attracted to the atoms in the balloon.”

The second chunk represented a new state of the paper, i.e., the paper was moving and then sticked to the balloon. When describing the second chunk, the student did not identify either new entities or the other elements of MR. The student describing the target phenomenon instead. That is, the paper moved to the balloon when these two had been placed next to each other. As the student mentioned in line 62 and 70, due to the attraction among unseen particles, “in the next frames [points to Frame 11 and 12], the paper goes off, because of, this is positive [points to the paper] and this is negative [points to the balloon]” (line 62), “then they [the little pieces of paper] move toward [the balloon]” (line 70).

4.3.2 The case from Student 1: SMA supports MR in Phase B

The case of Student 1, also exemplified by the case from Student 4, show that when Student 1 used his SMA creation (see Figure 5) for reasoning, his reasoning about electrostatic phenomena in Phase A was yet not classified as MR. He only identified entities without specifying activities of these entities (see Figure 4). However, his reasoning in Phase B exhibited MR.

Table 4 contains Student 1’s utterances conveying how the student constructed an SMA model of Phase A (Frame 12 to 25; see Figure 5 for example frames) and used this model to generate reasoning. The student represented the model as two sequential chunks. The first chunk depicted a state of the balloon at the microscopic level that has no unseen particles; see Frame 13. The second chunk illustrated the new state of the balloon at the microscopic level, that is, unseen particles gradually appeared in the balloon, see Frame 22 and 23.

When illustrating the first chunk (line 27, 37 and 41), in line with our framework, the student described the target phenomenon together with identifying unseen entities but did not identify setup conditions, properties of entities, and organization of entities. The student argued that there were no microscopic particles at the beginning moment when the balloon was being rubbed against the hair: “it [the balloon] starts [rubbing] from around her shoulder to the head, and then from the left to the right” (line 27), “there is no positive or negative charges, but they, hhmm, the balloon has just, it is neutral” (line 41). Note that even though the student did not include the presence of electrons in his model, the student realized the existence of these electrons. Thus, we claimed that the student identified entities when addressing chunk 1.

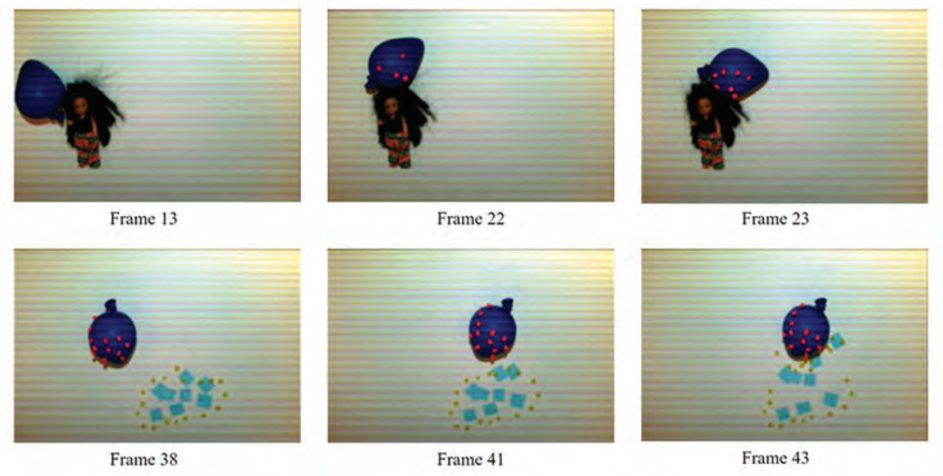


Figure 5. The example of frames from the animation created by Student 1; see Supplementary Animation S2 for the full frames and its animation.

Table 4. Student 1's utterances referring to Phase A

Line	Utterances	
27	S:	Yes, so it [the balloon] starts [rubbing] from around her shoulder to the head, and then from the left to the right [points to Frame 12 to 17 presenting the balloon being rubbed against the hair].
28	S:	The more she rubbed it [the balloon], the more pink Play-Doh particles start to appear [points to Frame 18 to 24]
37	S:	it [the balloon] starts [rubbing] [points to frame 13], it is above her head [points to Frame 16]. And the right. And then when she rubs it [the balloon] back [points to Frame 18], there is one positive charge [on the balloon].
38	R:	so you mean, starting from when you started rubbing it [the balloon; points to Frame 13]
41	S:	I think there is no positive or negative charges, but they, hhmm, the balloon has just, it is neutral. When you start rubbing it, it [the balloon] gets positive in this case
48	R:	Ok, so, where [do] these charges come from [points to pink clay sticking to the balloon]?
49	S:	Hmm, well, I know, when you start rubbing it, friction starts appearing. Maybe that energy forms into electrical charges, but that just assumption
53	S:	hmm, and well, the more she rubs it [the balloon], the more friction is created, and the more the electrical charges arise or rise, more particles appear [points to the pieces of pink clay on the balloon]

When illustrating the transition between Chunk 1 and Chunk 2, the student did not specify activities of entities (line 37 and 41). The student only described electrons gradually appearing on the balloon, without explaining how these electrons appeared.

As shown in line 37, the student said that "[…] And then when she rubs it [the balloon] back [points to Frame 18], there is one positive charge [on the balloon]".

In the second chunk (line 28, 37), the student described the change in target phenomenon, in the sense of the state of the balloon at the microscopic level, together with identifying new unseen entities. The student argued that when the balloon was being rubbed against the hair, at some point unseen particles gradually appeared on the balloon. As he mentioned, "The more she rubbed it [the balloon], the more pink Play-Doh particles start to appear" (line 28).

Even though the interviewer asked the student to specify activities of entities (see the excerpts in line 48), the student did not assign any activities to the entities. Instead, he responded to this prompt by proposing new abstract entities, e.g., "energy […] electrical charges" (line 49). Again, there were no activities referring to the new entities in order to allow his ideas of an abstract phenomenon "the more she rubs it [the balloon] … more particles appear " (line 53) to happen. Additionally, when describing the second chunk, the student did not identify properties of entities, setup conditions, or organization of entities.

Table 5 shows Student 1's utterances illustrating how the student constructed an SMA model of Phase B (Frame 31 to 41; see Figure 5 for example frames) and used his model creation for reasoning. The model was represented into two sequential chunks. These sequential chunks represented a state of microscopic particles on the balloon and on the little pieces of paper, and also depicted the change in the state of the position of the paper relative to the position of the balloon.

Table 5. Student 1's utterances referring to Phase B

Line	Utterances	
78	S:	then the balloon moves to the right, hmm, to the paper [points to Frame 37 to 40 presenting that the balloon starts moving to the paper]
79	S:	when it [the balloon] comes close [to the paper] [points to Frame 41], it's above, hmm, the pile is changing in form, some paper, part [of the] paper is attracted to the balloon, because of opposite charges [points to pieces of yellow clay on the balloon and pink clay on the balloon]
87	S:	well, ya, some [of] the closest paper particles are attracted to the balloon, and move to the balloon [points to Frame 42 to 44]
89	S:	because the balloon has positive charges, and the papers have negative charges, and different charges are attracted each other
92	S:	well, hmm, at the end, the most, [the] closest paper particles are attracted to the balloon, and the rest stays where it is [points to Frame 44]
93	R:	Why […] ?
94	S:	I think it is a matter of how close it is and also the power of the positive charges of the balloon
96	S:	hmm, well, if, I think, if the charges, or the opposite charges from the paper is closer, then it will be attracted more, because the force is bigger
98	S:	the force between the part of charges, different charges

99	S:	and it also like that, hmm, with I think, how big the force, hmm, how big the charges of the balloon, like if it [the balloon] is bigger, it would attract more pieces of paper with the account of charges
105	S	well, I think by rubbing it more. But eventually, it won't increase the force. So you can rub it, but if you do it like for an hour, it won't be bigger than for ten minutes or something, it has maximum like I said

When delineating the first chunk (line 78 and 79), in line with our framework, the student described the target phenomenon. That is, when "the balloon moves to the right, hmm, to the paper" (line 78), the little pieces of paper remained in their original position, as confirmed in line 92 and 94. The student also identified unseen entities, setup conditions, and properties of entities. As the student mentioned in line 89, "the balloon has positive charges, and the papers have negative charges" (line 89). Additionally, he identified the other entities, "the power of positive charges" (line 94) and "force" (line 96). Also, the properties of entities "force" were identified, i.e., "how big the force, hmm, how big the charges of the balloon […]" (line 99). However, organization of entities was not identified.

When illustrating the transition between Chunk 1 and Chunk 2, the student specified activities of entities: "some paper, part [of the] paper is attracted to the balloon, because of opposite charges" (line 79), and continued in line 89, "because the balloon has positive charges, and the papers have negative charges, and different charges are attracted each other".

In the second chunk, the student described the change in the target phenomenon. As the student said in line 79, when the balloon was close to the paper, "[…] some paper, part [of the] paper is attracted to the balloon […]". Additionally, he argued that "some [of] the closest paper particles are attracted to the balloon […]" (line 87), and "[…] [the] closest paper particles are attracted to the balloon, and the rest stays […]" (line 92). While describing the second chunk, the student did not identify new entities, setup conditions, properties of entities, or organization of entities.

When illustrating the sequence of these two chunks, the student exhibited chaining. As the student mentioned in line 96 and 99, "the opposite charges from the paper is closer, then it will be attracted more, because the force is bigger" (line 96), "[…] how big the force, hmm, how big the charges of the balloon, like if it [the balloon] is bigger, it would attract more pieces of paper with the account of charges" (line 99).

4.3.3 Guiding questions added to students reasoning to promote higher levels of MR

Table 6 contains the utterances of Student 5 reasoning about Phase B. The utterances show the moment that the student exhibited chaining after guiding questions were added to her reasoning. Initially, the student argued that frames 10 to 12 were considered to be two sequential chunks in which the first chunk represented a state of microscopic particles on both the balloon and on the paper, and the second chunk represented the state of these particles when the paper and the balloon were placed next to each other; see the descriptions of Table 3 for Student 5's initial ideas.

Table 6. The utterances presenting guiding questions added to Student 5's reasoning about Phase B

Line	Utterances	
73	R:	I see, this is the beginning [frame 10] when the balloon will move to the papers, right??
75	R:	And this one, it [some little pieces of paper] doesn't move [frame 12]?
76	S:	yeah, no, it's just like when you hold the balloon, and it's like when it's here [the moment when the balloon is still far away from the paper], it [the balloon] doesn't move yet, but I just want to have, to take, so it shows you that the balloon is moving towards it [the paper]
79	R:	so, my question, why when this position [point to Frame 10 and 11] the paper cannot be attracted to the balloon and starts moving when the balloon is here [frame 12]?
80	S:	yeah, well, the like, if it's too far away, then the attraction between is not strong enough to cover such a distance, but if you bring it [the balloon] closer, then it [the paper] starts moving. So it's too far away earlier
81	R:	What do you mean "strong enough"?
82	S:	Hmm, well, like there is only, the it's only two negative [point to the paper], the, the bottom one's only positive with, yeah two positive [frame 12] and, hmm, the top one [the balloon] is only two negative. And if it [the balloon] was like a higher number, then maybe it would have been stronger, hmm, the attraction yeah.
93	R:	[…] why these two [pieces of] paper stay on this position?
94	S:	because maybe, the paper that was already on the balloon balanced out, like by the paper moving on the balloon, the electrons change again, that some of these electrons went here [the electron from the paper sticking to the balloon moves to the balloon], and then maybe they both [the paper and the balloon] became negative or neutral again, so these last few [little pieces of] paper couldn't move
95	S:	or maybe this paper [point to the paper that does not move] didn't have enough of, this piece of paper didn't have, maybe they were neutral or maybe they weren't positive enough to be able to get there [move to the balloon], like so that yeah hmm

Guiding questions were then posed to prompt the student to articulate and reflect on her SMA creation by re-inviting her to think about other sequential chunks that had not yet been considered. As shown in lines 73, 75, and 79 (Table 6), guiding questions were posed for the student to think about both unconsidered sequential chunks: Chunk 1 represents a state of both the balloon and the little pieces of paper in which some of the pieces of paper remained in their original position (see line 73), Chunk 2 represents a new state of the paper in which some pieces of paper start moving to the balloon when the paper and the balloon are close enough (see line 75 and 79).

By providing this kind of prompt, therefore, the student was able to reach the highest level of MR, i.e., chaining, together with identifying properties of unseen entities. As illustrated in line 80 and 82, the student said that "then the attraction between is not strong enough to cover such a distance" (line 80) and "the, the bottom one's only positive with, yeah two positive [frame 12] and, hmm, the top one [the balloon] is only two negative. And if it [the balloon] was like a higher number, then maybe it would have been stronger" (line 82).

5. Discussion

5.1 RQ1: To what extent do students exhibit MR in reasoning at microscopic levels when engaging in constructing SMA?

The findings show that tasking students to construct an SMA contributes to developing MR. As shown in the diagram, engaging students in SMA construction appears to foster the ability to use MR. Some students initially did not use MR when explaining electrostatic phenomena. However, after creating an SMA, all students' reasoning exhibited the basic elements of MR. In addition, the students kept using MR when asked to explain similar electrostatics phenomena. Moreover, students used more elements of MR to reason about electrostatic phenomena after constructing SMA.

Students' transfer skills (Dori & Sasson, 2013; Sasson & Dori, 2012), which refer to "the ability to apply cognitive gains from one learning situation to another learning situation" (Dori & Sasson, 2013; p.369), were fostered during SMA creation. The results show that when students used their own SMA about electrostatic phenomena to reason, their reasoning exhibited MR; When students were tasked to explain the same electrostatics phenomenon as illustrated in their own SMA and to explain another similar phenomenon, they exhibited what is referred to as near transfer tasks (Dori & Sasson, 2013; Sasson & Dori, 2012), as they all were able to transfer the use of MR.

5.2 RQ2: What is a plausible mechanism for the promotion of elements of MR during the construction of SMA?

The empirical findings show that all students in our sample were able to construct an SMA displaying two separate phases labelled Phase A and Phase B. When discussing these phases, all students exhibited the basic elements of MR, i.e., entities and activities of entities.

A fine-grained analysis found that the fundamental aspects of SMA construction played a crucial role in supporting students in developing these basic elements of MR. That is, constructing the sequence of chunks played a role mainly in facilitating students to identify entities responsible for electrostatic phenomena whereas sequencing the chunks, in terms of thinking about the transition between the sequential chunks, appeared to elicit students' specification of activities of these entities.

Such empirical evidence is in line with our theoretical framework. We conjecture that the fundamental aspects of SMA construction, i.e., chunking and sequencing, support students' MR. Chunking and sequencing is a natural extension of drawing-based modeling and appears to evoke specific questions that foster identifying elements of MR. In terms of chunking, constructing chunks entails thinking about, as Gravel (2009) argued, "what is exactly changing?" from chunk 1 to the next chunks. Such questions encourage students to identify a state of a target phenomenon as one chunk and the new state of the phenomenon as the next chunk, thereby, as we illustrate in our theoretical framework (see Figure 1), involving elements of MR. As shown in the case of Student 5, when creating the first chunk of Phase A, the student addressed the initial state of the balloon, before it was rubbed against the hair. This implies the introduction of microscopic entities, since the balloon is not visibly changed by rubbing against the hair. The student constructed the second chunk to depict the new state of the balloon in terms of new unseen entities, e.g., by introducing an additional number of electrons.

Besides chunking, sequencing these chunks implies that students need to think about the transition between the sequential chunks by addressing particular questions, i.e., "why and how the change from a state to the new state happens?", thereby, as we illustrate in our framework (Figure 1), encouraging students to specify entities of activities. As the case of Student 5, when illustrating the transition between two sequential chunks illustrating the change in the state of the balloon, i.e., from neutral to charged, the student specified the causes for the transition, and thus the activities of the entities involved.

Our findings also point to a potential role for guiding questions as students reasoned with their own SMA creation. That is, doing so contributed to fostering the higher levels of MR, e.g., chaining. Note that all students who were given such question had exhibited MR, and due to such questions their MR developed. Also, such questions are not aimed at introducing students to elements of MR. In our study, guiding questions were intended to point out the other sequential chunks that students had not considered yet. Quintana et al. (2004) stress the benefit of providing guidance to facilitate articulation and reflection on what students have learned during sense making. In our study, as shown in the case of Student 5, guiding questions re-invited the student to reflect on and articulate the other sequential chunks depicting a state of the paper's position relative to the position of the balloon. By thinking about the new sequential chunks, the student's MR developed, i.e., chaining.

The findings in our current study give credence to the body of literature showing that students benefit from learning by constructing models (e.g., Andrade et al., 2021; Cooper et al., 2017). While previous studies have shown the value of student-constructed SMAs, for instance, to learn science concepts (e.g., Hoban et al., 2011; Nielsen et al., 2022; Nielsen & Hoban, 2015), to generate discussion (see Mills et al., 2019), our study provides further insight into how SMA construction supports MR.

Previous research has indicated that engaging students in constructing SMAs promoted MR (Bachtiar et al., 2021; Wilkerson-Jerde et al., 2015; Wilkerson et al., 2018). The findings in our current study add the knowledge to the field by emphasizing that students' engaging in constructing chunks and sequencing these chunks (by thinking about the transition between the sequential chunks), led students to employ the basic elements of MR, i.e., identifying entities and activities of entities. It is precisly these elements that were found to be the most challenging elements that students need to involve in when developing MR (Bachtiar et al., 2022).

It should be noted that the results in our studies are not intended to claim that tasking students to construct an SMA is the only, or even the best, way to support MR. We acknowledge that students' MR could be supported by other types of modeling, such as drawing-based modeling (Andrade et al., 2021; Cooper et al., 2017). We think that SMAs-based modeling, like other modeling approaches, has unique affordances in order to support MR.

5.3 Implications for instruction

Our study has shown that reasoning with students' own SMA creation is valuable to MR. Particularly, our study theoretically and empirically show that chunking and sequencing does play a role in promoting students' MR. Our empirical findings also suggest some aspects that should be considered. Based on these findings, we make some practical suggestions as to the implementation of learning with the construction of SMA for supporting MR.

First, given that building an SMA involves creating a series of individual images, called frames, when reasoning with their own SMA creation, students might naturally focus on each frame, rather than the transitions among them. Therefore, we suggest that the design of SMA should sufficiently encourage students to think about the transitions rather than only the separate frames. Second, when the process of creating an SMA is concerned with learning activities, such activities should encourage students to not only create a series of frames, but also to challenge them to explicitly relate a certain frame to the previous and/or subsequent frames.

Third, our study noted that some students did not connect one chunk to the next chunks, thereby leading to miss the identification of some elements of MR. To address this case, while our study examined the creation of SMAs by individual students, students working in groups may be beneficial. Andrade et al. (2021) showed that drawing activities in a collaborative environment supported students' enactment of MR because it provided opportunities to infer and negotiate more ideas.

Finally, a set of questions posed by teachers may be fruitful to help students link the sequential frames. In the case of static electricity, for instance, in which the second frame presents unseen particles in the balloon whereas the first frame has none, students could be asked questions such as “where do these particles come from?” or “how do these particles get inside the balloon?”. Our findings also showed the benefits of asking questions intended to point to the sequential frames that students did not yet consider when reasoning. Posing such questions helps students develop the higher levels of MR, e.g., chaining, as shown in the case of Student 5 who was asked the question: “why can the paper not be attracted to the balloon in this position [point to Frame 10 and 11], but starts moving when the balloon is here [frame 12]?”. This suggestion implies further research to discover how teachers can effectively pose such questions to larger groups of students, as our study involved few students.

5.4 Limitations and implications for future research

As with any study, the present research has certain limitations. Given the fact that our study was conducted in a laboratory setting, rather than a classroom setting, further research on the implementation of SMA in real classroom is needed. Further studies should also address, such as whether peer interaction during SMA construction activities is necessary, how teachers can support students during the SMA construction process. These further studies may provide a deeper insight into how teachers can provide support students as they learn about science in groups by creating an SMA. The relatively small sample size and the nature of case studies are an issue when generalization is concerned. The general goal of case study methodology is not generalizability but rather to dive deeply into explanations for a particular phenomenon (Gustafsson, 2017; Stake, 2013; Yin, 2013); in particular, our study was aiming at mechanisms rather than at quantitative data. Future studies should increase the number of research participants to arrive at quantitative data on the level of MR reached by students creating an SMA. This could shed light on how students arrive at using the higher-ranking elements of MR in Russ' classification.

In our current study, students' development of MR was based solely on the role of the nature of SMA construction. We did not yet consider other factors, such as the characteristics of individual students, e.g., prior knowledge, familiarity with the tasks. We acknowledge that such factors probably also influence students' SMA construction activities, thus affecting students' MR. This needs to be further investigated.

Our findings show that adding guiding questions to students' activities in articulating and reflecting on their own SMA creation contributes to fostering the higher levels of MR, e.g., chaining. While such question prompts are intended to invite students to think about the unconsidered sequential frames, we do not yet see a pattern of which types of questions could be used to lead students to reach chaining. Having more student cases in future research is needed to obtain further insight into the role of such question prompts in students' development of MR, particularly chaining.

Lastly, our present study focused on physics domain. We believe that the utility of SMAs-based modeling could be applied to other domains, as shown by Berg et al., (2019) in chemistry, Mills et al. (2019) in geology, and Orraryd and Tibell (2021) in biology. Therefore, future research should address other science domains. We also suggest future studies exploring different contexts, e.g., related electricity subjects such as electric current, and other science domains that require reasoning at microscopic levels. This further research could lead to more general guidelines on how to employ SMA in the science classroom.

5.5 Conclusions

Our study shows that engaging students in the construction of SMA that serves as modeling and a cognitive tool contributes to promoting MR. This study revealed theoretically and empirically that both chunking and sequencing as the construction nature of SMA do play a role in students' development of MR. As a theoretical perspective, our study proposes a framework that can unveil possible links between such construction nature of SMA and elements of MR. Such a theoretical framework is also confirmed by empirical evidence showing that students were identifying elements of MR when engaging in both chunking and sequencing. Additionally, guiding questions that help students articulate and reflect on their ideas of sequential chunks contributed to fostering the higher levels of MR, e.g., chaining. Also, the results found that such SMA activities have a potential effect on students' retention of MR. Finally, we suggest some pragmatic recommendations that should be considered when implementing SMA activities as pedagogical instruction to support MR.

CHAPTER 5 Fostering students' mechanistic reasoning in physics: Learning by constructing stop-motion animations

This chapter is based on:
Bachtiar, R. W., Meulenbroeks, R. F. G., & van Joolingen, W. R. Fostering students' mechanistic reasoning in physics: Learning by constructing stop-motion animations. (in preparation)

Abstract

This study explores the implementation of Stop motion Animation (SMA) construction activities in a science classroom. It addresses the conditions under which student-created SMAs contribute to developing mechanistic reasoning (MR). An exploratory study was conducted involving 41 ninth-grade students working in groups to construct an SMA about electrostatic phenomena. Storyboards, SMAs, and students' written responses before and after constructing SMA were collected and analyzed. The analysis showed that students' exhibiting MR was associated with the quality of an SMA as judged according to a certain design, i.e., (1) the sequence from one chunk to the next in an SMA depicts the change in a state at microscopic levels, and (2) the transition between these chunks is explicitly described. Implications on how to implement the construction of SMAs as a pedagogical approach in a classroom to support students in developing MR are discussed, e.g., explicitly challenging students to address lower scale levels in their SMAs.

Keywords

Mechanistic reasoning, stop-motion animation, slowmation, physics, static electricity

1. Introduction and background

There is ample evidence that science students benefit from constructing models (e.g., Ainsworth et al., 2011; Prain & Tytler, 2012; Tytler et al., 2020; Van Meter & Garner, 2005). We address one type of dynamic models, viz., stop-motion animation (SMA), for which its value in science learning has been positively evaluated in a number of studies (Farrokhnia et al., 2020). Benefits of student-generated SMAs that have been found are fostering conceptual understanding (Mills et al., 2019; Nielsen et al., 2020a), encouraging to engage with science content (Brown et al., 2013; Hoban, 2020; Orraryd & Tibell, 2021), promoting discussions (Hoban & Nielsen, 2014; Mills et al., 2019), and facilitating the construction of scientific explanations (Berg et al., 2019; Hoban et al., 2011; Nielsen et al., 2020b). Creating SMAs as a learning approach promoted students' interest in learning science and geology (Mills et al., 2020), advanced their communication skills (Deaton et al., 2013; Fridberg & Redfors, 2018) and increased intrinsic motivation for science (Kamp & Deaton, 2013; Vratulis et al., 2011).

Although SMA construction activities have advantages, its implementation in a classroom setting has proved to be challenging. Wishart (2017) pointed to the need for the appropriate preparations, e.g., making sure that the SMA software works properly, and students know how to use it. Furthermore, studies point out that constructing an SMA is a time-consuming process (Berg et al., 2019; Hoban, 2005; Hoban & Nielsen, 2014; Orraryd & Tibell, 2021). Berg et al. (2019) found that students spent a lot of time and effort on the SMA constructed as part of their practical work. Mills et al. (2019) pointed out that, compared to adults such as university students who are more autonomous learners, secondary school students need more teacher support during the construction of an SMA. Nielsen & Hoban (2015) suggested comparing students' SMA creation with correct expert-constructed models to scaffold students to build scientific knowledge.

As an effort to deal with these challenges, we pay particular attention to the fundamental aspects of SMA construction activities, i.e., chunking and sequencing (Bachtiar et al., 2021; Hoban et al., 2011). In particular, we seek to understand whether and how these aspects support students in developing mechanistic reasoning (MR).

MR refers to the ability to provide mechanistic explanations of a target phenomenon by describing the interactions between (visible and invisible) entities (Bachtiar et al., 2022). Following Russ and colleagues (2008), we draw on seven elements to identify students' MR about the phenomena. These seven elements are: (1) describing the target phenomenon, (2) identifying setup conditions, (3) identifying entities, (4) identifying activities of entities, (5) identifying properties of entities, (6) identifying organization of entities, and (7) chaining (Russ et al., 2008, p. 512-513). Of these elements, entities and activities of the entities are the basic elements that need to be included when generating MR (Bachtiar et al., 2022). In addition, MR includes entities at (at least) one scale level below the scale level of a target phenomenon (Bachtiar et al., 2022; Krist et al., 2019). For example, MR about the behavior of ideal gases necessarily involves descriptions of atomic particles as entities.

Earlier research has shown that engaging students in constructing an SMA can stimulate MR (Bachtiar et al., 2021; Wilkerson-Jerde et al., 2015; Wilkerson et al., 2018). Bachtiar et al. (2023) proposed a theoretical framework to illustrate the link between the construction nature of SMA, i.e., chunking and sequencing, and elements of MR. Our study here contributes to extending this line of research by focusing on the question of "If so, under what conditions?", subsequently the following research questions (RQs):

- RQ1: What are the characteristics in terms of form and content of SMAs created by students in a science class?
- RQ2: How does the creation of SMA contribute to students' MR about electrostatic phenomena?

2. Methods

2.1 Research context and participants

Our present study focuses on the role of student-constructed SMAs in a science class in supporting students' development of MR. This study involved 43 tenth-grade students (aged 14 – 16 years) from three different classes and two different teachers at an urban international school in the Netherlands. Given the age of the students, informed consent from the parents and the students was obtained for video and audio recordings. Both teachers had more than 10 years of physics teaching experience. The first author had meetings with the teachers to introduce the study and set up the physics lesson on static electricity, in the classroom. The first author acting as a researcher and the teachers worked together during the lesson, with very different tasks. The teachers were in charge of the lesson plan, including the introduction of basic knowledge on static electricity to students. The researcher only provided guidance in the process of constructing an SMA.

2.2 Research design and data collection

The study was conducted during three 90-minute-lessons. Table 1 gives the lesson plan. During the lesson, a camera was positioned in the front and at the back of the classroom. In each class, two smaller groups of students were also recorded separately from a closer distance.

Table 1. The lesson plan

Stages	The lesson activities	Data collected
1. Demonstration	A group of two or three students do a simple electrostatic experiment, guided by the teacher.	--
2. Pre-test	Students individually answer questions about the subject.	41 student pre-tests
3. Creating an SMA	Two or three students work together (20 groups in total) to make a storyboard and create an SMA.	20 artifacts containing a storyboard and an SMA for each

Stages	The lesson activities	Data collected
4. Whole-class discussion	One volunteer group presents an SMA; the other groups respond with their observations and comments.	--
5. Post-test	Students individually answer questions relating to a video about electrostatics.	41 student post-tests
6. Transfer test	Students individually answer a further question relating to the video about electrostatics.	41 student transfer tests

The six stages of the lesson are as follows:

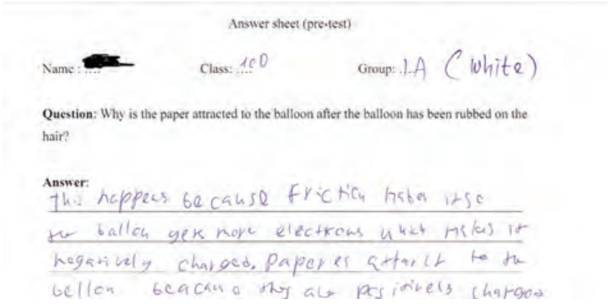
Stage 1: Demonstration

This stage began with tasking two or three students to work together in a group (20 groups in total) to do a simple electrostatic experiment, i.e., rubbing the balloon against the hair and then moving the balloon towards small pieces of paper. The teacher was also provided with a video of the experiment, in case the experiment in the classroom would fail, e.g., due to high ambient humidity.

Stage 2: Pre-test

First, the students were introduced to some basic knowledge about static electricity: (1) matter is made of atoms that are composed of electrons and protons, (2) electrons can move freely (3) protons and electrons have positive and negative charges, respectively, and (4) like charges repel and opposite charges are attracted each other.

The students were then tasked individually to provide the written answers to a pre-test on the experiment they had just witnessed. Figure 1 gives examples of the test questions and students' answers. The answers were provided by 41 of the 43 students in this study.



Answer sheet (pre-test)

Name : [redacted]   Class: 10D   Group: 1A (White)

Question: Why is the paper attracted to the balloon after the balloon has been rubbed on the hair?

Answer:
This happens because friction between the
the ballon gets more electrons which makes it
negatively charged. Paperes attract to the
bellon beacause they are positively charged

Figure 1. An example of a pre-test question and student answer

Stage 3: Working together to construct a storyboard and corresponding SMA

20 groups of students (17 dyads and three triads) were tasked to construct an SMA about the experiment they witnessed. The available materials were the balloon,

play-dough clay, small pieces of paper, a doll with fake hair, and the SMA software. Constructing an SMA started with a storyboard, in which students were asked to visualize their intended SMA. Each group was asked to make drawings in a square blank "frame" and to provide the written descriptions of the drawings. Figure 4 gives an example of a storyboard.

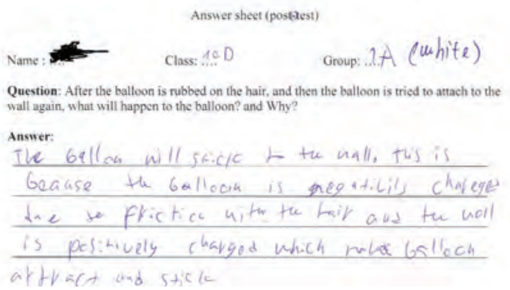
The second step in constructing an SMA was to make an animation product based on the plan represented in the storyboard. Using Stop Motion StudioTM, students were tasked to take digital photographs; they included annotations in these photographs, and recorded a narration to the final SMA. Note that neither the teacher nor the researcher provided any conceptual assistance at this stage, only technical support. At the end of the second stage, in total, 20 storyboards and 20 animations were collected.

Stage 4: Whole-class discussion

A whole-class discussion was held for all groups to give and receive peer feedback. This step was conducted by asking a group to present their animation and then letting the other groups respond to the animation. Note that not all SMAs were shared in this way, only one, and on a voluntary basis.

Stage 5: Post-test

In this stage, the students watched a video about a different electrostatic phenomenon, i.e., an electrically charged balloon sticking to a wall after it has been rubbed against someone's hair. This video was paused at specific time frames and the students were tasked to individually provide a written response to the questions, i.e., "after rubbing the balloon against the hair, will the balloon stick to the wall? Why?" This question is referred to as the post-test because basically the questions in pre- and post-tests are identical; see Figure 2 as an example of the post-test.



Answer sheet (post-test)

Name : [redacted] Class: 1e D Group: 2A (white)

Question: After the balloon is rubbed on the hair, and then the balloon is tried to attach to the wall again, what will happen to the balloon? and Why?

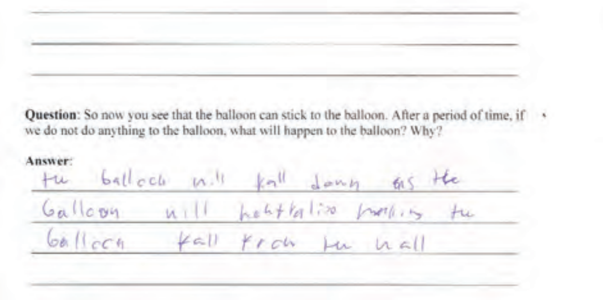
Answer:

The ballon will stick to the wall, this is
Because the balloon is negatitily charged
due to friction with the hair and the wall
is positively charged which make balloon
attract and stick

Figure 2. An example of a post-test question and student answer

Stage 6: Transfer test

After the students finished answering the post-test question, they continued watching the video, which is watched in Stage 5, until the end, and then were tasked to work individually to provide the written answers to further questions on electrostatics, e.g., "If we do not do anything to the balloon, will the balloon fall down or keep sticking to the wall? Why?" We assigned these questions to a transfer test because the question differed from either the post-test or pre-test; Figure 3 provides an example of the transfer test. At the end of the lesson, 41 students' written answers to the post- and transfer test were collected.



Question: So now you see that the balloon can stick to the balloon. After a period of time, if we do not do anything to the balloon, what will happen to the balloon? Why?

Answer:
the balloon will fall down as the
balloon will neutralize making the
balloon fall from the wall

Figure 3. An example of a transfer test question and student answer

2.3 Data analysis

The following data sources were used to address the research questions: 41 students' written answers in each pre-, post-, and transfer test, and 20 sets of artifacts (each including a storyboard and an SMA).

To address RQ1, we first analyzed the storyboards and SMAs in terms of the presentation and the overall content. In analyzing the storyboards, we examined: (1) the number of frames, (2) whether written text was included in the frames, and (3) the inclusion of microscopic particles, e.g., electrons. Analyzing SMAs included recording: (1) the duration, (2) the number of frames, whether or not (3) narration and/or (4) annotations were included, and whether microscopic particles were illustrated in the SMA.

The content analysis of the storyboards and the SMAs focused on how electrostatic phenomena was represented. All storyboards and the SMAs in the sample shared a similar two-part structure, which will be referred to as Phase A and Phase B. Phase A refers to the moment when the balloon is being rubbed against someone's hair, and Phase B refers to the moment when the balloon approaches the small pieces of paper.

The content analysis went on to a fine-grained analysis applied to both the storyboard and the SMAs, in terms of how the frames (in either a storyboard or an SMA) referring to either Phase A or B were ordered. To do so, for the storyboards, we examined drawings and written text. Note that this analysis can only be applied to storyboards containing more than one frame (which was the case for all storyboards save one). For the SMAs, we investigated visuals, annotation and narration.

Two criteria were applied to the fine-grained analysis. First, were the frames organized in chunks and did the sequence from one chunk to the next depict the change in a state at microscopic levels? Second, was the transition between these chunks explicitly described? To accomplish this analysis, we determined which set of frames could be considered to be one chunk. One or more adjacent frames constitute one chunk when these frames depict one specific state of a target phenomenon at microscopic levels. The next frames could be considered to be the subsequent chunk (consisting again of one or more frames) when these frames depict a new state of the target phenomenon. Thus, the sequence from the first chunk to the second chunk, for instance, illustrates the change in the state of the target phenomenon at microscopic levels. For example, in the case of electrostatic phenomena, the first chunk depicts a balloon with two electrons, while the second chunk represents the increase in the number of electrons in the balloon. The transition from one chunk to the next chunk was labeled “explicit” when there was an explicit specification addressing “how” the change from one chunk to the next one could happen. For example, as in the aforementioned case, the transition between these two sequential chunks was specified by providing a written text in a frame “while the balloon rubbed […] the electrons from the doll are transferred into the balloon.”

To address RQ2, we started with identifying elements of MR (in terms of Russ’ scheme, as indicated above) in student’s written responses to the tests. Specifically, students’ answers to both the pre-test and the post-test were categorized into either Phase A or Phase B. Note that not all students addressed both phases in their answers. For example, consider Student 4A’s answer to the pre-test: “Because the balloon has a negative charge which is caused by having more electrons than protons.” We assigned this student’s answer to Phase B only.

The analysis went on to investigate the contribution of the SMA creation to students’ MR. To do so, each student’s answers to the tests, i.e., the pre-, post-, and transfer tests, was labeled either MR or non-MR, based on the presence (or absence) of both Element 3 and 4 in the answers. Cross-case tabulation was then conducted between the analyses of MR versus non-MR and the content analysis of SMA.

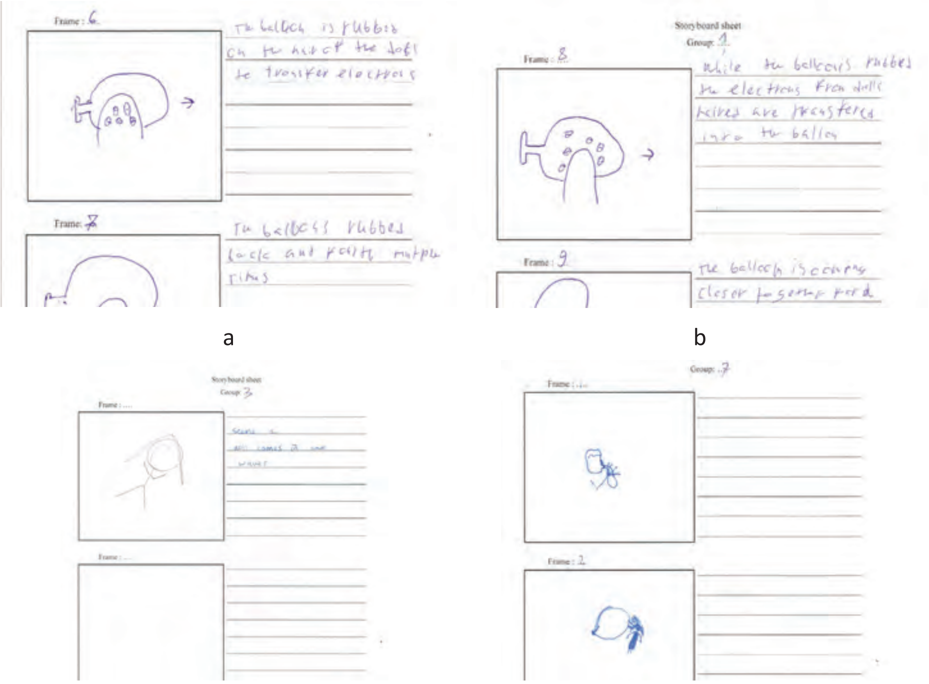
3. Results

3.1 The characteristics of student-generated SMAs about electrostatic phenomena

This section reports on the results of analyzing 20 groups of students’ storyboards and SMAs in terms of presentation and content. In general, the presentation of each of the 20 storyboards varied; see Appendix 1 for the summary of the results. A storyboard contained a number of square boxes, called “frames”, ranging from one (Group X3, X4, and Z4) to 11 (Group X1 and Y1); see Figure 4 as an example of the frames from a storyboard. Seventeen out of 20 groups (e.g., Group X1) made drawings in the frames together with providing written explanations of the drawings; see Figure 4a, b, and c as an example. In the other groups (i.e., Group Z1, Z4, and Z7), the frames in their storyboard included drawings without the written text, e.g., Figure 4d.

From the analysis of the presentations, the storyboards also demonstrated a large variety of approaches and levels of depth. The storyboard in 14 groups (e.g., Group X1; Figure 4a and b) included the drawings of microscopic particles, e.g., electrons. On the contrary, there were no illustrations of such particles in the storyboard in six groups, i.e., Groups X3, X4, Y1, Y2, Z4 and Z7; see Figure 4c and 4d as an example. Although the frames from the storyboard in four out of these six groups (e.g., Group X3) contained drawings accompanied by some written text, they did not address any physics concepts; see Figure 4c as an example. In addition, among these six groups, four groups (i.e., Groups X3, X4, Z4 and Z7) had a storyboard that was made up of one or two frames (see Figure 4c and 4d as an example), which can hardly be categorized as a storyboard.

Concerning the results from analyzing the presentation of SMAs, the SMAs are different in time length, ranging from 4 s (Group X5) to 28 s (Group Y2); see Appendix 2 for the summary of the results. An SMA was built from a number of frames that are equal to the time length (e.g., Group X1), or more than the time length (e.g. Group X3); see Figure 5 as an example of a frame. Twelve groups (out of 20) added an annotation to the frames and 17 groups (out of 20) inserted a narration in their SMA.



a

b

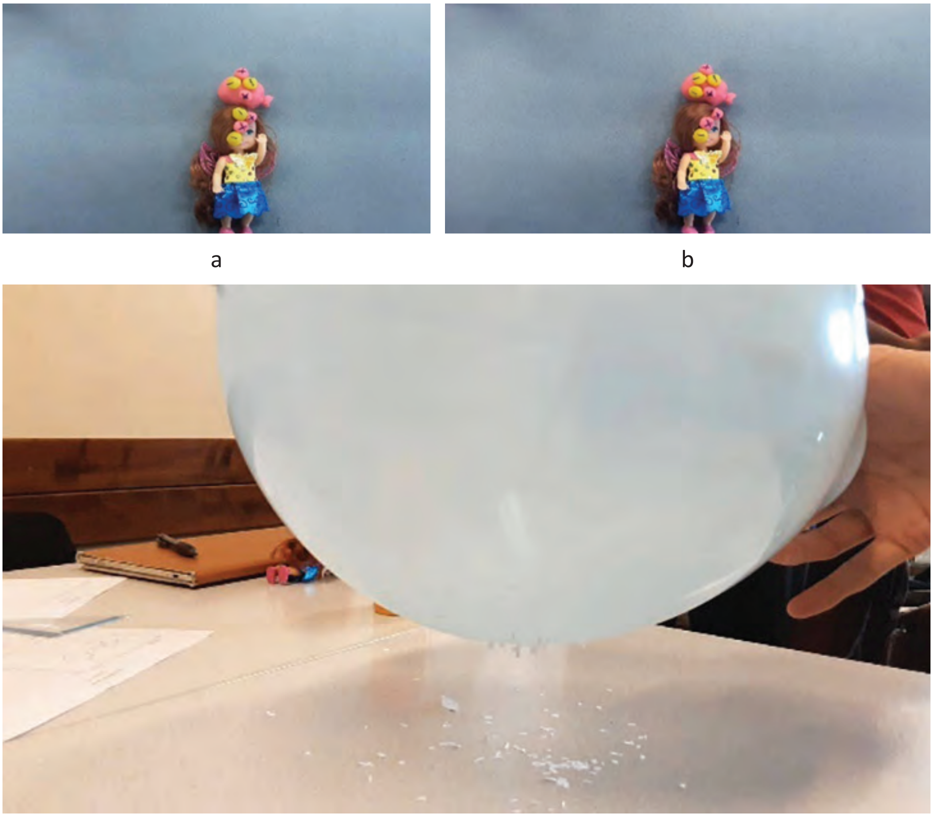
c

d

Figure 4. Example of the frames from storyboards made by Group X1 (a and b), Group X3 (c) and Group Z7 (d)

The analysis of the presentations also showed that the SMA in 19 out 20 groups (e.g., Group Z1) illustrated microscopic particles, e.g., electrons; see Figure 5a and 5b as an example. Among these 19 groups, 18 used the small pieces of clay as a model for such particles. In one of these 19 groups (i.e., Group Y1), the depiction of atomic particles was described using narration instead of visual displays. One SMA out of 20 groups, i.e., Group Y2, did not illustrate such atomic particles; see Figure 5c.

In relation to the content analysis of the storyboards and the SMAs, overall, all groups made a storyboard and continued to construct an SMA to illustrate electrostatics phenomena. The phenomena were represented in two phases, i.e., when rubbing a balloon against someone's hair (Phase A) and then bringing the balloon to the small pieces of paper (Phase B).



a b

c

Figure 5. Screenshots of the frames in the SMA made by Group Z1 (a and b) and Group Y2 (c); see Appendix 4 for the animations.

Table 2 presents the results of analyzing the content of storyboards and SMAs, respectively, focusing on each phase.

Concerning storyboard, as shown in Table 2, focusing on Phase A, seven out of 20 groups (e.g., Group X1) made a storyboard meeting Criteria 1 and 2, the four groups' storyboard met Criterion 1, and the storyboard in 9 groups did not meet both criteria. Focusing on Phase B, the storyboard in four groups fulfilled both criteria (e.g., Group X7) and the five groups' storyboard fulfilled Criterion 1, and the rest of the groups did not meet both criteria. See Appendix 3 for the results of content analysis of storyboards by each group.

Table 2. The number of groups whose the design of either storyboard or SMA met the criteria; 20 groups of students in total.

	Storyboard		SMA	
	Phase A	Phase B	Phase A	Phase B
Meeting Criteria 1 and 2	7	4	9	6
Meeting Criterion 1, not Criterion 2	4	5	10	12
Meeting Criterion 2, not Criterion 1	0	0	0	0
Not meeting Criteria 1 and 2	9	11	1	2

The first criterion refers to the order of the frames in a storyboard that were organized in the sequence of chunks to represent the change in the state of microscopic particles, e.g., electrons. The second criterion attends to the storyboard providing the explicit description of the transition between these chunks. For example, in the storyboard focusing on Phase A created by Group X1, see Figure 4a, the first seven frames represented the first chunk depicting a balloon with no electrons, and the next eight frames as the second chunk represented electrons appearing in the balloon (Figure 4b).

Concerning the content analysis of SMAs, as shown in Table 2, an SMA in 9 groups (for Phase A) and 6 groups (for Phase B) met both Criteria 1 and 2. Ten groups (for Phase A) and 12 groups (for Phase B) created an SMA meeting only Criterion 1. In the rest of the groups, their SMA did not meet either criterion. See Appendix 3 for the results of content analysis of SMAs by each group.

The first criterion in SMA refers to the order of the frames that made up the SMA representing the sequence of chunks that depicted the change in the state of a target phenomenon at microscopic levels. The second criterion refers to the explicit descriptions of the transitions between these chunks. For example, in the SMA of Phase A created by Group Z1 (Figure 5a and b), the frames were ordered in terms of the sequence of two chunks illustrating the change in the states of the balloon and the hair at microscopic levels (Criteria 1). The first chunk represents the initial state of both the balloon and the hair at the microscopic level, that is, there are an equal number of electrons and protons in either the balloon or the hair (see Figure 5a). In the second chunk representing the new state, the balloon had more electrons than protons while the number of electrons in the hair decreased (see Figure 5b). The sequence of these two chunks was then described (Criteria 2) in terms of narration added to the SMA by stating that "the electrons from the hair transfer to the balloon so that makes the balloon negatively charged."

3.2 MR in pre-, post- and transfer test with respect to the creation of SMA

Figure 6 presents the total number of students involving elements of MR in the written answers of pre-, post- and transfer test. Looking at the basic elements of MR, 39, 41, and 40 students' answers of pre-, post-, and transfer test, respectively, exhibited Element 3 (entities). Also, Element 4 (activities of entities) was identified in 23, 27, and 24 students' answers of pre-, post-, and transfer test, respectively. However, no clear patterns are visible in the results of these tests.

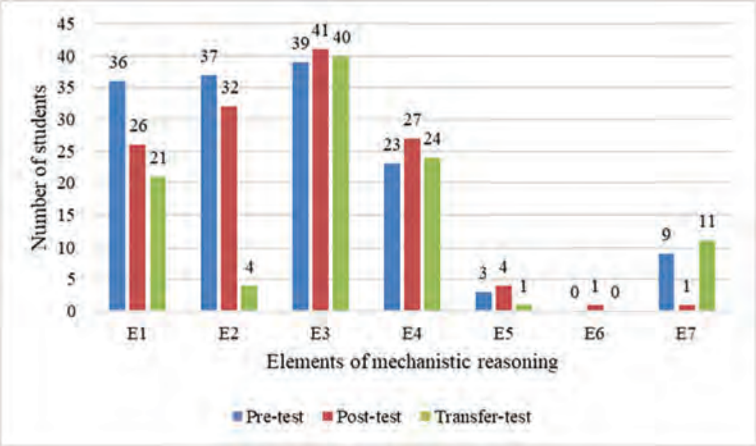


Figure 6. The elements of MR identified in students' written answers; E1 to E7 refer to the terms of elements of MR in Russ et al. (2008).

The following Tables 3, 4, 5 and 6, focusing on Phase A and Phase B, respectively, present the results of the cross-case tabulation analysis intended to investigate possible associations between the quality of SMA and MR. The quality of SMA refers to an SMA meeting both Criteria 1 and 2.

Based on Table 3, focusing on Phase A, among the groups of students who did not exhibit MR in the pre-test (7 groups), only one group has an SMA meeting both criteria. Among the groups of students in which at least one of the students in the group exhibited MR in the pre-test (13 groups in total), eight groups have an SMA meeting both criteria. The Chi square test between the quality of SMA and MR, focusing on Phase A, was not significant ($X^2(2)=3{,}624$; $p=0{,}1633 > 0{,}05$).

Focusing on Phase B, among the groups in which at least one of the students in the group exhibited MR (9 groups in total), five groups have an SMA meeting both criteria. For the groups in which none of students in the group exhibit MR (11 groups in total), only one group had an SMA meeting both criteria. The Chi square test between the quality of SMA and MR, focusing on Phase B, was significant ($X^2(2)=7{,}508$; $p=0{,}0234 < 0{,}05$).

Table 3. Cross-case tabulation between students’ MR in the pre-test and the design of SMA, focusing on Phase A and B. (Note: the cells with numbers refer to the number of groups and there are either 2 or 3 students in a group. Students demonstrating MR refer to those involving Elements 3 and 4 in their answers of the pre-test; SMA meeting the criteria refers to the design of SMA meeting two criteria; see Section 2.3 for the description of these criteria)

		Phase A		Phase B	
		SMA meeting both criteria	SMA not meeting both criteria	SMA meeting both criteria	SMA not meeting both criteria
MR specific to Phase A in the pre-test	All students in the group	2	2	-	-
	None of the students in the group	1	6	-	-
	Not all students in the group	6	3	-	-
MR specific to Phase B in the pre-test	All students in the group	-	-	2	0
	None of the students in the group	-	-	1	10
	Not all students in the group	-	-	3	4

Table 4. Cross-case tabulation between the design of SMA in Phase A and students’ MR specific to Phase A in the post-test. (Note that the cells with numbers in Tables 4 to 6 indicate the number of students; 26 out of 41 students refer to Phase A in the post-test).

	Students demonstrating MR	Students not demonstrating MR
SMA meeting the criteria	10	4
SMA not meeting the criteria	2	10

As shown in Table 4, among those students whose SMA in Phase A met two criteria, more students exhibited MR in the post-test specific to Phase A (10/14) than those students who did not (4/14). Also, more students did not demonstrate MR (10/12) when their SMA did not meet these criteria. The Chi square test is significant (X^2(2)=7,797; p=0,0052 < 0,05), thus implying that there is association between the quality of SMA and MR in the post-test, focusing on Phase A.

Based on Table 5, 11 of 12 students whose SMA in Phase B met two criteria exhibited MR in the post-test specific to Phase B, and one student did not demonstrate MR. Among 29 students whose SMA of Phase B did not meet either criterion, nine students demonstrated MR whereas 20 students did not. The Chi square test is significant (X^2(2)= 12,489; p=0,0004<0,05), thus implying that there is an association between SMA design and MR in the post-test, focusing on Phase B.

Table 5. Cross-case tabulation between the design of SMA in Phase B and students' MR in the post-test specific to Phase B.

	Students demonstrating MR	Students not demonstrating MR
SMA meeting the criteria	11	1
SMA not meeting the criteria	9	20

Table 6. Cross-case tabulation between the design of SMA in both phases (i.e., Phase A and Phase B) and students' MR in the transfer test.

	Students demonstrating MR	Students not demonstrating MR
SMA in Phase A and B meeting the criteria	8	2
SMA in Phase A meeting the criteria, but not in Phase B	4	5
SMA in Phase B meeting the criteria, but not in Phase A	2	0
SMA in Phase A and B not meeting the criteria	10	10

Based on Table 6, there are ten students whose SMA in both phases met two criteria. Among these ten students, eight students' reasoning in the transfer test was identified as MR. Among 20 students whose design SMA in both phases did not meet the criteria, half of them demonstrated MR in the transfer test. Among 11 students whose SMA met the criteria in one of two phases, four out of nine (for Phase A) and two (for Phase B) demonstrated MR in the transfer test. The Chi square test is not significant ($X^2(3)=4{,}651$; $p=0{,}1992 > 0{,}05$), meaning that there is no association between the quality of SMA and MR in the transfer test.

4. Discussion and conclusion

4.1 RQ1: What are the characteristics in terms of presentation and content of storyboards and SMAs created by students in a science class?

The first research question was addressed by analyzing storyboards and SMAs in terms of presentation and content.

In terms of the presentation, students' storyboards and corresponding SMAs show a large diversity in terms of number of frames (1-11 for the storyboard, 4-104 for the SMA), and corresponding annotation or narration. Most of the groups of students sketched microscopic particles, e.g., electrons, in the storyboard. Also, the majority of SMAs (19 out of 20 groups) did include such microscopic particles.

In terms of the content analysis, all storyboards and corresponding SMAs depicted electrostatic phenomena and addressed two phases of the experiment they are supposed to model, i.e., when rubbing a balloon against someone's hair (Phase A) and bringing the balloon towards the small pieces of paper (Phase B).

A fine-grained analysis showed that most of the groups of students represented the model of electrostatic phenomena, in either a storyboard or its corresponding SMA, in terms of the sequence of two chunks depicting the change in the state of microscopic particles. The storyboard and its corresponding SMA in some of these groups of students provided the description of the transition between these chunks that is intended to specify why and how the change could happen.

As exemplified in an SMA, the first chunk depicted an equal number of electrons and protons in the balloon. The next chunk represented that the number of electrons and protons was no longer equal. A narration was also added to this SMA to describe the transition between these two chunks by stating that "the electrons from the hair transfer to the hair so that makes the balloon negatively charged."

4.2 RQ2: How does the creation of SMA contribute to students' MR about electrostatic phenomena?

The findings indicate that the quality of SMA plays a role in supporting students' exhibiting MR. The quality of SMA was related to a specific design, i.e., (1) the sequence from one chunk to the next in an SMA depicts the change of a state at microscopic levels, and (2) an SMA provides explicit descriptions of the transition between these chunks.

The framework we developed could demonstrate why and how the nature of SMA construction, i.e., chunking and sequencing, supports MR (Bachtiar et al., 2023). In this framework, both chunking and sequencing promote particular elements of MR, including entities and activities of entities. the nature of SMA construction, i.e., chunking and sequencing

These findings also provide a new insight into our framework. While the framework illustrates that constructing and sequencing chunks elicit particular elements of MR, our current findings emphasize that one chunk and the next should be sequenced in such a way that two adjacent chunks, for instance, depict the change of a state at microscopic levels.

These findings also add new knowledge to the literature exploring the role of SMA construction activities in supporting MR. While the studies, e.g., Wilkerson et al. (2018) and Bachtiar et al. (2021), provided empirical evidence that engaging students in constructing MR stimulated them to use MR, our current study adds that the way an SMA is constructed under a certain design also matters. Another study, by Krist et al. (2019), points out that to guide students' construction of MR, students should be directed to think at scale levels below the scale level of a target phenomenon, and to identify and unpack the relevant factors at such levels. Our current study has shown that students indeed engaged in thinking at such levels when constructing an SMA model of electrostatic phenomena.

Science education scholars (e.g., Braaten & Windschitl, 2011; Clement, 2013; Mathayas et al., 2021) regard such an SMA model as “explanatory models,” a kind of scientific model visualizing the activities of unseen entities to explain why and how an observable phenomenon occurs. Explanatory models are valuable for students “provide explanations for different phenomena across many contexts” (Braaten & Windschitl, 2011; p. 649).

The findings in our current study showed that the quality of SMA exhibiting such explanatory models was associated with students’ MR in the post-test, but there was no association between the quality of SMA and students’ MR in the transfer test.

One possible explanation for these findings could be attributed to what Dori and Sasson (2013) call students’ transfer skills, as “the ability to apply cognitive gains from one learning situation to another learning situation” (p. 369). According to Dori & Sasson (2013), the tasks in the post-test and in the transfer test could be considered “near transfer” and “far transfer”, respectively, implying that “the difficulty of a transfer task increases as we move away from” (p. 370) near transfer to far transfer. Therefore, we conjecture that for those students who did not generate MR in the transfer test, their knowledge or skills, which were acquired during the SMA construction activities, were not sufficient to construct MR in the transfer test.

4.3 Practical implications

Based on the findings in this study, we make practical suggestions about what to consider when implementing SMA construction activities as a learning approach to support students’ MR.

First, it is a necessary condition for all students to have the same base-line content knowledge in the beginning. In our case, the teacher provided a PowerPoint presentation to introduce students to the basic concepts in static electricity. Alternatively, students could conduct observations through an internet search or watching videos (Hoban et al., 2011; Hoban & Nielsen, 2013).

Second, the sequence from one chunk to the next from an SMA creation should depict the change in the state of a target phenomenon at microscopic levels. To do so, students should be encouraged to think at lower scale levels when constructing a series of frames forming an SMA. For instance, when creating the first frame considered to be the first chunk (note that one chunk can consist of one or more frames), this frame should present a state of a target phenomenon at microscopic levels. In the case of electrostatic phenomena, for instance, this first frame as Chunk 1 presents the balloon that has four electrons. When constructing the next frames as the second chunk, this second chunk represent a new state of the target phenomenon at microscopic levels, e.g., the balloon now has six electrons. Thus, the sequence from the first chunk to the second chunk depicts a change at microscopic levels in terms of an increase in the number of electrons. Therefore, this SMA not only displays a balloon that is being rubbed against someone’s hair, but also represents a change in the state of the balloon at microscopic levels, i.e., additional electrons in the balloon. To support students in thinking at such lower scale levels, teachers could also provide questions, e.g., what is exactly changing from one chunk to the next chunks in terms of a state at microscopic levels?

Third, an SMA creation should provide the description of the transition from one chunk to the next chunks. Students could be tasked to provide such descriptions in the form of narration or annotation added to their SMA. As exemplified above, i.e., the sequence of two chunks represents the increase in the number of electrons in the balloon, the description of the transition between these two chunks could be: "when rubbing the balloon against the hair, electrons in the hair move to the balloon." To support students in thinking about such transition, teachers could also provide questions, e.g., why and how does the number of electrons in the balloon increase?

Finally, we suggest that when students engage in discussions, either a peer discussion during the process of constructing an SMA, or a classroom discussion intended to reflect on and discuss their SMA product, they should discuss two topics related to the particular design of an SMA i.e., whether and how (1) the sequence from one chunk to the next depicts the change in a state of a target phenomenon at microscopic levels, and (2) the transition between these chunks, which is intended to specify how and why the change happens, is described. We also suggest that teachers should facilitate such discussions, as the study by Lowell et al. (2022) showed that teacher intervention was crucial to class discussions.

4.4 Limitations and future research

We recognize limitations in our current study. The fact that our study involves a relatively small group of students (N=40) has led us to qualitative analysis. The students in our study were all in one school with no students from other schools, so it might be possible that the results are biased. In our data analysis, we did not consider gender and age, thus constituting possible sources of bias.

In this study, we suggest that teachers should facilitate either peer or class discussions. The fact that this study was set up with minimal teacher intervention calls for further research to gain more understanding about how teachers' interventions are conducive to a productive peer or class discussion, when and in which moments teacher should intervene in discussions, thereby improving the quality of SMA.

The present study also found that students' MR was associated with an SMA constructed in a certain design. We acknowledge that the quality of SMA could be attributed to other aspects, such as the number of frames, and frame rates, thereby the need to be explored further.

In our study, we found the same number of students who generated MR in the transfer test as students who did not, with regard to those students whose SMA did not meet the criteria. This implies the need for a further clinical interview study for those students to gain more insight into the role of an SMA model in supporting students in explaining other similar phenomena.

Given that the data analysis in this study did yet not consider the correctness of students' answers to the tests, we suggest that future studies explore the link between the quality of SMA and the correctness of explanations. Therefore, by gaining such an understanding, we could propose implications from such studies in terms of how the construction of SMA supports students in developing scientifically correct reasoning.

We also recommend our study should be extended to other subjects, e.g., kinematics, or electric current, so that we could gain more insights into how and under what conditions the construction of SMA contributes to developing students' MR in a broader context.

The data in our study show that the SMAs were created in different numbers of frames (from 4 to 103). These frames were set in different frame rates, i.e., one frame per second, or more than one frame per second. Learning about static electricity, as the case in our study, does not fully depend on a typical set of frame rate. In kinematics (for example), this is very different. Thus, we suggest a future study exploring how the construction of SMA helps students learn about kinematics, such as accelerated motion.

CHAPTER 6 Discussion and conclusion

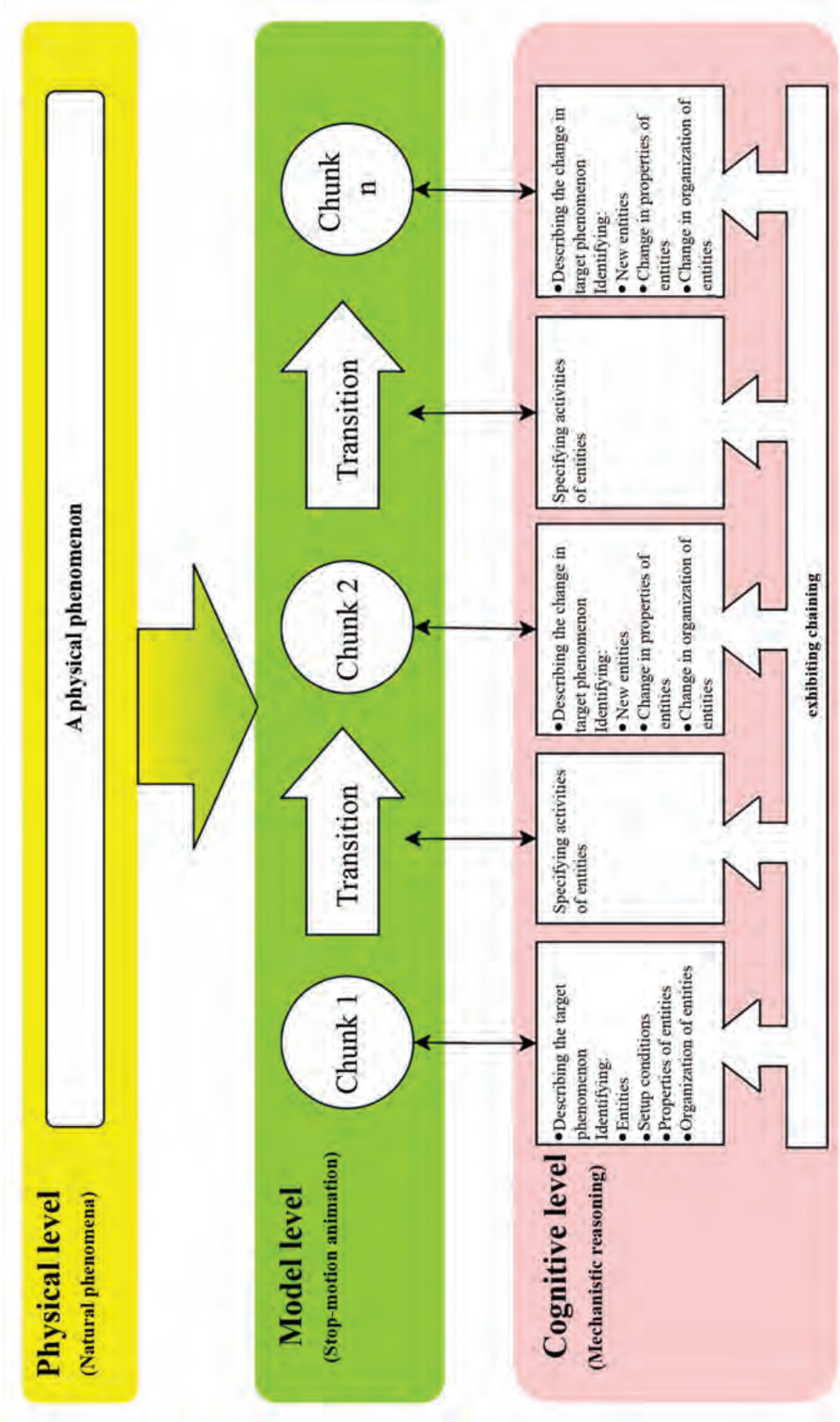


Figure 1. A theoretical framework for cognitive processes in SMA construction

This chapter starts with answering the main research question, and followed by providing implications for educational practices and future research.

1. Answering the main research question

The research questions of the four separate studies have been addressed in the previous chapters, i.e., in Chapter 2 to Chapter 5. Drawing on the findings in these four studies, we now revisit and answer the main research question of this dissertation:

> *How can student-constructed stop-motion animations (SMAs) be used as a pedagogical approach to support students in developing mechanistic reasoning (MR)?*

Our review study (Chapter 2) concluded that generating MR entails thinking about causal mechanisms: MR needs to address which causes lead to which effects. However, MR does more than illustrate cause-effect relationships. MR also needs to describe the underlying processes of how causes give rise to effects. The description of such processes necessarily includes two elements, i.e., entities and activities of entities, which are the basic elements of MR, and these entities may often be at scale levels below the observable.

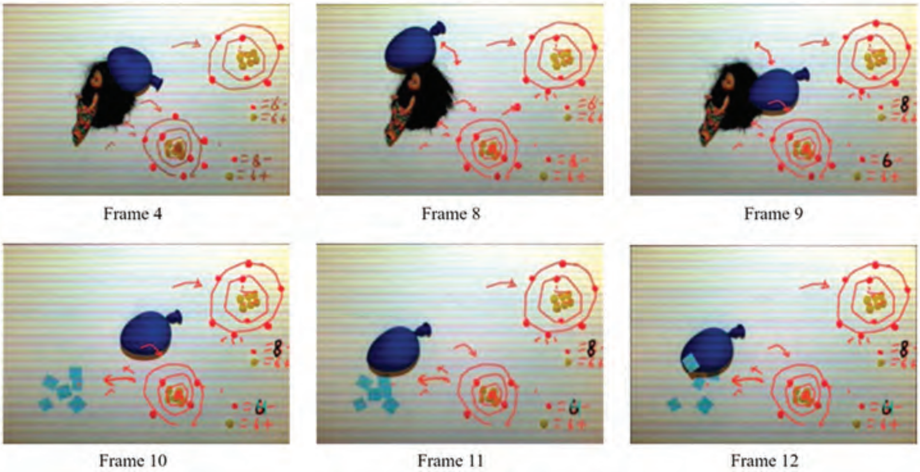
Identifying and using these two basic elements are common challenges for students in developing MR. To support students in dealing with such challenges, our studies adapted one type of strategies identified in our review study, i.e., engaging students in constructing and using their own models. In particular, our studies focused on one type of dynamic models, i.e., stop-motion animations (SMAs) for several reasons. First, constructing an SMA model does not require knowledge of programming code or mathematical formalisms, thereby benefitting younger students, such as the target age group in our studies, i.e., ages 16-18. Second, because our studies focus on the content of physics topics that mostly convey a process, e.g., motion, SMA supports in visualizing dynamic processes.

The findings in our studies show that engaging students in constructing an SMA supports them in developing MR. We were able to substantiate this claim by providing a theoretical perspective (Chapter 4) and empirical evidence (Chapters 3, 4, and 5).

The theoretical perspective crystallized in a framework illustrates how the nature of SMA construction, i.e., chunking and sequencing, promotes the elements of MR; see Figure 1. This framework presents the interconnection of three levels, i.e., the physical level, the model level, and the cognitive level, and highlights the principal elements of SMA construction, i.e., chunking and sequencing. SMA is thus serving as a modeling and a cognitive tool.

In this framework, creating a series of frames forming an SMA, constitutes the process of modeling a physical phenomenon. An SMA model is represented in terms of a sequence of chunks. Each of these chunks represents a state of the physical phenomenon. In addition, the sequence from one chunk to the next depict the change in the state of a target phenomenon. Figure 2 shows an example of an SMA presenting the ball's motion resembling a curved trajectory (the topic in Study 2; Chapter 3). This SMA conveys a model of the movement of the ball. This SMA model is represented in terms of several chunks in sequence. Each chunk represents a particular position of the ball during its movement. As another example, an SMA model of electrostatics phenomena (the topic in Study 3 and 4) is represented in a sequence of two chunks, see Figure 3. Each chunk depicts a state of both the balloon and the hair at microscopic levels, i.e., a certain number of electrons and protons. In addition, the order of the first chunk and the second chunk illustrates the change in the number of these atomic particles. Note that one chunk can consist of one or more frames. In our study on parabolic motion (Study 2), one frame usually equaled one chunk, while in the case of electrostatics phenomena (Study 3 and 4), one chunk usually consisted of more than one frame.

Figure 2. A screenshot of an SMA representing a model of the ball movement. This picture overlays all frames forming the SMA. Each frame presents one particular position of the ball; the detailed descriptions of this SMA model are addressed in Chapter 3



Frame 4
Frame 8
Frame 9
Frame 10
Frame 11
Frame 12

Figure 3. The frames from an SMA conveying electrostatics phenomena

Constructing an SMA model by chunking and sequencing evokes certain cognitive processes. That is, constructing and sequencing chunks evoke specific questions that need to be addressed through identifying the elements of MR. Constructing two chunks in sequence, for instance, entails thinking about one state (for Chunk 1) and the new state (for Chunk 2) of a target phenomenon by addressing questions: “What is happening?” in each chunk, and “What is exactly changing?” from Chunk 1 to chunk 2. Addressing such questions involves identifying the particular elements of MR (as illustrated in our framework; see Figure 1), including entities. Sequencing these two chunks entails thinking about the transition between these chunks by questioning “why and how the change happens”, thereby encouraging students to identify the other basic element of MR, i.e., activities of entities.

Study 3 (Chapter 4) provided initial evidence confirming our framework by showing that all students engaging in chunking and sequencing ended up using at least the basic elements of MR, i.e., entities and activities of these entities. For instance, one student created an SMA model of electrostatics phenomena in terms of the sequence of only two chunks, see Figure 3. These chunks illustrated the change in the state of the balloon at microscopic levels before and after rubbing it against someone’s hair, i.e., by illustrating the change in the number of either electrons (entities). In addition, the sequence of these two chunks illustrated the activities of these entities in terms of the movement of electrons.

In relation to the other empirical findings, Study 2 reported that all students in the study demonstrated MR, as evidenced by the presence of the basic elements of MR, i.e., entities and activities of entities, when explaining their own SMA model of the ball’s motion. The fact that the SMA model was represented in terms of the sequence of the ball’s different positions during its movement seems to stimulate the students to ask questions such as “what it is exactly that is changing?” from the first position of the ball to the next position and “why and how does the position change?”, when thinking about these chunks. These questions reflect the cognitive level in our framework. Thinking about the first two chunks (Figure 2) led the students to introduce “the foot” as an entity in the beginning position (as the first chunk) and to specify activities of this entity, i.e., “kicked the ball” to enable the ball to move from the ground to a certain height (as the second chunk). Moreover, when thinking about the sequence from the second chunk to the next chunk (Figure 2), the students introduced other entities referring to abstract concepts, such as gravity, and an activity of the entity gravity, i.e., “pulls the ball down” to enable the ball to continue its ascent with a change of its direction.

The findings in Study 4 (Chapter 5) show that students’ development of MR was associated with the quality of an SMA model as evidenced in two main criteria. That is, (1) the sequence from one chunk to the next in an SMA model represents the change in the state of microscopic particles, and (2) the transition between these chunks is explicitly described.

The empirical findings in Study 2 and 3 point to the essential role of constructing and sequencing the chunks in supporting the development of MR. The findings in Study

4 give an additional insight into what should be represented in the chunks, i.e., a state at microscopic levels, and how to sequence these chunks, i.e., by explicitly describing the transition between these chunks. Figure 4 gives an example sequence of two chunks in an SMA model of electrostatics phenomena related to a balloon being rubbed against hair. The sequence of two chunks depicts the change in the state of microscopic particles, i.e., from equal number of electrons and protons (Figure 4a) to the increase (for the balloon) or decrease (for the hair) in the number of these atomic particles (Figure 4b). The description of the sequence of these chunks is illustrated in terms of the movement of electrons from the hair to the balloon.

Figure 4. Screenshots of an SMA representing a model of electrostatics phenomena depicting the sequence of two chunks.

2. Implications for educational practices

Based on our work, we offer some practical suggestions on how to implement SMA construction activities in science learning for supporting students' MR.

First, it is necessary for all students to have the basic content knowledge before embarking on the design of an SMA, especially involving abstract contents of physics. For example, in the case of static electricity (Study 3 and 4), the relevant basic concepts, such as electrons as negative charges, need to be introduced. We suggest that teachers introduce the basic concepts of static electricity through, for instance, providing a PowerPoint presentation or handout. Alternatively, students could be tasked to search for information online or to watch educational videos (Hoban et al., 2011; Hoban & Nielsen, 2013).

Second, we suggest that while constructing an SMA, students should be prompted to think at lower scale levels. To do so, given that creating a series of frames forming an SMA implies constructing the sequence of chunks, students should be tasked to construct each of the chunks that represent a state of a target phenomenon, also at microscopic levels. In addition, the sequence from one chunk to the next should include the change in the state of the target phenomenon at such levels. In other words, with one chunk illustrating a state at microscopic levels the subsequent chunk should depict the "new" state at such levels. For example, in the context of electrostatics phenomena, if one chunk illustrates some number of electrons on a balloon, and the next chunk should depict an increase in the number of electrons on the balloon. To support students in doing so, teachers could provide guiding questions, i.e., “What exactly is changing?” from the first chunk to the next chunks in terms of a state of the balloon at microscopic levels. Students could be also tasked to think about a state of the balloon at microscopic levels when they make a storyboard. In the storyboard, students should be tasked to make drawings of such a state together with providing written text.

Third, given that an SMA is built from several individual frames (forming chunks), in a specific order, when constructing an SMA, students should be challenged to explicitly think about the transition between these chunks. Given that the sequence of two chunks, for instance, depicts the change of a state at microscopic levels, the transition is intended to illustrate why and how the change happens.

To help students do so, students could be tasked to explicitly relate one chunk to the previous and/or subsequent chunks by describing the transition from one chunk to the next. Students could do so by adding narration or annotation to their SMA. As exemplified in the case of electrostatics above, the narration could be: “When rubbing the balloon against the hair, electrons in the hair move to the balloon.” To support students in thinking about such a transition guiding questions could be provided, e.g., “Why and how does the number of electrons on the balloon increase?”. Also, students could be also asked to illustrate and to describe the increase in the number of electrons when they make drawings and write text in the storyboard.

Fourth, we suggest a collaborative environment in the process of SMA construction to open up a peer discussion and a classroom discussion to reflect on and discuss the resulted SMA product. Particularly, we suggest that teachers should facilitate the discussion, focusing on two topics related to the design of SMA, i.e., (1) the sequence from one chunk to the next represents the change in a state at lower scale levels of a target phenomenon, and (2) the transition between these chunks depicts the descriptions of how and why the change happens.

3. Implications for future research

Our studies have shown that student-constructed SMAs as a pedagogical approach supports students’ MR. The fundamental aspects of SMA, i.e., chunking and sequencing, play a crucial role in supporting students in developing MR. Other aspects that were not yet addressed, such as the limitations of our studies, and the insights that were obtained give rise to a number of future research directions.

The findings in Study 4 provide a first insight into the implementation of the construction of SMA in a classroom setting. The findings suggest that students’ development of MR was associated with the quality of SMA. This study did not yet consider other aspects that may influence the quality of SMA (such as the number of frames), a learning environment (e.g., a time-limit for the process of SMA construction), and individual characteristics of participants (e.g., prior knowledge, and a familiarity with SMA software). Therefore, further research exploring these concerns is needed.

Based on the findings in Study 3 and 4, we point out the role of teachers in SMA construction activities. We have suggested which types of questions teachers may ask when students are creating an SMA. Also, teachers should facilitate student discussions. However, our studies were set up with minimal or no teacher intervention. This calls for further research on finding out, for instance, how teachers' interventions are conducive to a productive peer or class discussion, and at which moments teachers should intervene in discussions to improve the quality of SMA. Therefore, we may gain more insight into how teachers could effectively facilitate the process of constructing SMAs.

Our framework (Figure 1) provides a theoretical perspective on how chunking and sequencing promote the elements of MR. This framework needs to be put into practice and tested further so that we might gain more insight into how the framework could be translated into practical activities.

Our studies have shown that students used MR when reasoning with their own SMA creation. In this case, the classification of whether students' reasoning is mechanistic was not based on correctness, but only on the elements of MR. Further research is needed to find out how the construction of SMA could be designed into a learning approach that facilitates students' progress with canonically accepted reasoning.

In our studies, the benefits of SMA were concerned with the chronology and causality of events, meaning that students gain benefits from constructing and thinking about what happens in each of the chunks and how the transition from one chunk to the next happens. We did not yet consider another important feature of SMA, i.e., frame rates and number of frames. For example, as shown in Study 4, SMAs were created with different numbers of frames (from 4 to 103) and were set in different frame rates, such as one frame per second or three frames per second. We suggest future studies exploring how a typical set of frames may be of benefit to students who learn about subjects, such as kinematics, e.g., accelerated motion.

Overall, our studies have shown that MR is essential for students learning science, but students need support in this process. A theoretical perspective and empirical evidence have been provided to show that engaging students in constructing an SMA model supported them in developing MR. Therefore, we argue that the work in our studies has provided insights into efforts to foster students' scientific literacy by engaging them in scientific practices, in terms of constructing and using models, in the form of stop-motion animations, to construct scientific explanations in terms of mechanistic reasoning.

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Appendices

Appendix to Chapter 2

APPENDIX A

An overview of the selected articles

Note:

[1] NA = not specified

[2] Conceptualisations: the studies (N:30) providing conceptualisations of MR; Adoption: the studies (N:13) making use of the conceptualisations of MR provided by the 30 studies; Student: the studies (N:17) that do not provide conceptualisations of MR, but exemplifying students who either exhibited MR or those did not.

[3] √ = studies that are assigned to Research Question (RQ) 2, 3 or 4.

No	Author(s)	Year	educational level1	Domain	RQ12	RQ23	RQ33	RQ43
1	Bachtiar, Meulenbroeks, & van Joolingen	2021	Lower secondary	Physics	Conceptualisations			√
2	Balabanoff, Al Fulaiti, Bhusal, Harrold, & Moon	2020	University	Physics	Student	√	√	
3	Becker, Noyes, & Cooper	2016	University	Chemistry	Conceptualisations	√	√	
4	Bolger, Kobiela, Weinberg, & Lehrer	2012	Elementary	Physics	Conceptualisations	√	√	√
5	Brown, Ronfard, & Kelemen	2020	Elementary	Biology	Student			√
6	Caspari, Kranz, & Graulich	2018	University	Chemistry	Conceptualisations	√	√	
7	Caspari, Weinrich, Sevian, & Graulich	2018	University	Chemistry	Adoption	√		
8	Cooper, Kouyoumdjian, Underwood, Kouyourndjian, & Underwood	2016	University	Chemistry	Conceptualisations	√	√	√
9	Crandell, Kouyoumdjian, Underwood, & Cooper	2019	University	Chemistry	Conceptualisations	√	√	√
10	Crandell, Lockhart, & Cooper	2020	University	Chemistry	Conceptualisations			√
11	Andrade, Shwartz, Freire & Baptista	2021	Lower secondary	Chemistry	Conceptualisations			√
12	Dickes, Sengupta, Farris, & Basu	2016	Elementary	Biology	Conceptualisations			√
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	√		

No	Author(s)	Year	educational level1	Domain	RQ12	RQ23	RQ33	RQ43
16	Haskel-Ittah & Yarden	2018	Upper secondary	Biology	Conceptualisations	√	√	
17	Haskel-Ittah, Duncan, Vázquez-Ben, & Yarden	2020	Lower secondary	Biology	Conceptualisations		√	
18	Haskel-Ittah, Duncan, & Yarden	2020	University	Biology	Conceptualisations	√		
19	Houchlei, Bloch, & Cooper	2021	University	Chemistry	Student	√		
20	Hsiao, Lee, & Klopfer	2019	In-service teachers	Biology	Adoption	√		√
21	Keiner & Graulich	2021	University	Chemistry	Conceptualisations			√
22	Keiner & Graulich	2020	University	Chemistry	Conceptualisations		√	
23	Krist, Schwarz, & Reiser	2019	Elementary	Multiple domains (biology and physics)	Conceptualisations			√
24	Louca & Papademetri-Kachrimani	2012	Kindergartens	Multiple domains (Physics and Mathematics)	Adoption			√
25	Macrie-Shuck & Talanquer	2020	University	Chemistry	Conceptualisations	√		
26	Mathayas, Brown, & Lindgren	2021	Lower secondary	Physics	Conceptualisations			√
27	Mathayas, Brown, Wallon, & Lindgren	2019	Lower secondary	Physics	Adoption			√
28	Moore, C.	2021	NA	Biology	Conceptualisations	√		
29	Moreira, Marzabal, & Talanquer	2019	Upper secondary students	Chemistry	Conceptualisations	√	√	
30	Nawani, von Kotzebue, Spangler, & Neuhaus	2019	Upper secondary	Biology	Student		√	√

No	Author(s)	Year	educational level1	Domain	RQ12	RQ23	RQ33	RQ43
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	Conceptualisations	√		
36	Russ, Scherr, Hammer, & Mikeska	2008	Elementary	Physics	Conceptualisations	√		
37	Scalco, Talanquer, Kiill, & Cordeiro	2018	University	Chemistry	Conceptualisations		√	√
38	Scherr & Robertson	2015	In-service teachers	Physics	Conceptualisations	√		
39	Schwarz, Ke, Lee, & Rosenberg	2014	Elementary	Physics	Student	√		
40	Scott, Anderson, Mashood, Matz, Underwood, & Sawtelle,	2018	University	Biology	Conceptualisations	√	√	
41	Sevian, Hugi-Cleary, Ngai, Wanjiku, & Baldoria	2018	University	Chemistry	Student	√	√	√
42	Southard, Espindola, Zaepfel, & Bolger	2017	University	Biology	Conceptualisations	√	√	
43	Southard, Wince, Meddleton, & Bolger	2016	University	Biology	Conceptualisations	√	√	
44	Speth, Shaw, Momsen, Reinagel, Le, Taqieddin, & Long	2014	University	Biology	Student		√	

No	Author(s)	Year	educational level1	Domain	RQ12	RQ23	RQ33	RQ43
45	Stevens, Shin, & Peek-Brown	2013	Multiple educational levels (Lower secondary and Upper secondary students)	Chemistry	Student	√	√	
46	Suarez & Otero	2014	Elementary	Physics	Student			√
47	Talanquer	2010	University	Chemistry	Student	√	√	
48	Talanquer	2018	University	Chemistry	Conceptualisations		√	
49	Tang, Elby, & Hammer	2020	Elementary	Physics	Conceptualisations			√
50	Tate, Ibourk, McElhaney, & Feng	2020	Lower secondary	Biology	Student	√	√	√
51	van Mil, Boerwinkel, & Waarlo	2013	NA	Biology	Conceptualisations			√
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	Conceptualisations		√	
54	Weinberg	2019	Multi-educational levels (Elementary to university students)	Physics	Adoption	√		
55	Weinberg (a)	2017	Multi-educational levels (Elementary to university students)	Physics	Adoption			√

No	Author(s)	Year	educational level1	Domain	RQ12	RQ23	RQ33	RQ43
56	Weinberg (b)	2017	Multi-educational levels (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	√	√	

Appendix to Chapter 3

A stop-motion animation about the ball motion:

https://link.springer.com/article/10.1007/s10956-021-09918-z

Appendix to Chapter 4

A stop-motion animation about electrostatic phenomena created by Student 1:

https://drive.google.com/file/d/1yA1--Dvjj6EK0SPFM8M_a44Y7FNmNWtJ/view?usp=sharing

A stop-motion animation about electrostatic phenomena created by Student 5:

https://drive.google.com/file/d/1T3nb26gWXCrGn1OjJNFxwIpva6tYd6wq/view?usp=sharing

Appendices to Chapter 5

Appendix 1

The results of analyzing the presentation of storyboard (Note: the letter X, Y, and Z refer to class, number 1 to 7 refer to group code, e.g., X1 refers to Group 1 in class X)

Group	The number of frames	The inclusion of drawings and written text	A sketch of microscopic particles
X1	11	Drawings and written text	Yes
X2	6	Drawings and written text	Yes
X3	1	Drawings and written text	No
X4	1	Drawings and written text	No
X5	4	Drawings and written text	Yes
X6	3	Drawings and written text	Yes
X7	6	Drawings and written text	Yes
Y1	3	Drawings and written text	No
Y2	11	Drawings and written text	No
Y3	6	Drawings and written text	Yes
Y4	5	Drawings and written text	Yes
Y5	7	Drawings and written text	Yes
Y6	3	Drawings and written text	Yes
Z1	7	Drawings	Yes
Z2	5	Drawings and written text	Yes
Z3	4	Drawings and written text	Yes

Group	The number of frames	The inclusion of drawings and written text	A sketch of microscopic particles
Z4	1	Drawings	No
Z5	4	Drawings and written text	Yes
Z6	3	Drawings and written text	Yes
Z7	2	Drawings	No

Appendix 2

The results of analyzing SMAs in terms of the forms (Note: see the caption on Table 1 for the descriptions of the symbols of a group name)

Group	Time length (second)	The number of Frames	Narration	Annotation	Inclusion of microscopic particles
X1	13	13	Yes	Yes	Yes
X2	8	8	No	Yes	Yes
X3	18	93	Yes	No	Yes
X4	12	12	No	Yes	Yes
X5	4	4	Yes	No	Yes
X6	14	14	Yes	Yes	Yes
X7	9	19	Yes	Yes	Yes
Y1	14	14	Yes	No	Yes
Y2	28	28	Yes	No	No
Y3	10	52	Yes	Yes	Yes
Y4	15	15	Yes	Yes	Yes
Y5	22	22	Yes	No	Yes
Y6	8	8	Yes	No	Yes
Z1	11	47	Yes	Yes	Yes
Z2	17	103	Yes	Yes	Yes
Z3	8	8	Yes	No	Yes
Z4	7	7	No	Yes	Yes
Z5	21	41	Yes	No	Yes
Z6	15	15	Yes	Yes	Yes
Z7	21	21	Yes	Yes	Yes

Appendix 3

The results of the content analysis of the storyboards and SMAs (Note: see Section 2.3 for the description of Criteria 1 and 2)

Groups	Storyboard				SMA			
	Phase A		Phase B		Phase A		Phase B	
	Criteria 1	Criteria 2	Criteria 1	Criteria 2	Criteria 1	Criteria 2	Criteria 1	Criteria 2
X1	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
X2	Yes	No	Yes	No	Yes	No	Yes	No
X3	No	No	No	No	Yes	No	Yes	No
X4	No	No	No	No	Yes	No	Yes	No
X5	No	No	No	No	Yes	No	Yes	No
X6	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes
X7	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Y1	No	No	No	No	Yes	Yes	No	No
Y2	No	No	No	No	No	No	No	No
Y3	Yes	No	Yes	No	Yes	No	Yes	Yes
Y4	Yes	yes	Yes	Yes	Yes	Yes	Yes	Yes
Y5	Yes	No	No	No	Yes	No	Yes	No
Y6	Yes	No	No	No	Yes	No	Yes	No
Z1	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Z2	No	No	No	No	Yes	Yes	Yes	No
Z3	Yes	Yes	Yes	No	Yes	Yes	Yes	No
Z4	No	No	No	No	Yes	No	Yes	No
Z5	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Z6	No	No	No	No	Yes	No	Yes	No
Z7	No	No	No	No	Yes	No	Yes	No

Appendix 4

Stop-motion animation made by Group Z1:

https://drive.google.com/file/d/1e1sJACswMJK-QmESVMzEI2NGwqhAD5hT/view?usp=sharing

Stop-motion animation made by Group Y2:

https://drive.google.com/file/d/1lcPgy1mbTcJsXVnQ2wqeH5e7AQnMvyGC/view?usp=sharing

Summary

Scientific literacy is one of the goals of science education. Students' scientific literacy could be promoted through engaging them in scientific practices. Mechanistic reasoning (MR) is a form of causal reasoning that is essential for students to construct scientific explanations, which is considered a type of scientific practices. However, developing MR is challenging for students. To support students in developing MR, our studies adapted an instructional approach, that is, tasking students to construct and use a model for reasoning, specifically a stop-motion animations (SMAs)-based model. Therefore, four separate studies were conducted to address the main research question:

> *How can student-constructed SMAs be used as a pedagogical approach to support students in developing MR?*

Study 1 (Chapter 2): Mechanistic reasoning in science education: A literature review

A considerable number of studies have focused on mechanistic reasoning (MR) in science education. This calls for a systematic synthesis. Thus, we conducted a literature review study aimed at finding out what is known about MR in science education research. The reviewed literature identified that MR could be seen as a type of causal reasoning that includes two basic elements, i.e., entities and activities of entities. The findings also showed that identifying entities and specifying activities of entities are categorized as the most difficult problems students face in developing MR. Various strategies were used to support students in developing MR. One of these strategies is to ask students to create and use a model for reasoning.

Study 2 (Chapter 3): Stimulating mechanistic reasoning in physics using student-constructed stop-motion animations

The second study aimed to find out whether and how engaging students in constructing an SMA model of the ball motion induced their MR. The findings showed that all students constructed an SMA to represent a model of the ball's movement that resembled a curved trajectory. When students used their own SMA to reason about the ball's motion, their reasoning exhibited MR, as evidenced by the fact that the basic elements of MR (i.e., entities and activities of entities) were involved. Moreover, students' abstract reasoning developed.

Study 3 (Chapter 4): Understanding how student-constructed stop-motion animations promote mechanistic reasoning: A theoretical framework and empirical evidence

This study sought to understand how the construction of SMAs promotes MR. A theoretical framework was developed to link the nature of SMA construction, i.e., chunking and sequencing, and seven elements of MR proposed by Russ et al. (2008). To examine the extent to which the framework was in line with empirical evidence, a multiple-case study involving students to construct a model of electrostatics phenomena was conducted.

Empirical findings confirmed the framework by showing that all students identified entities and activities of entities when engaging in chunking and sequencing. Chunking played a role in facilitating students to identify entities responsible for electrostatic phenomena, and sequencing seemed to elicit students to specify activities of entities to explain why and how the phenomena occur.

Study 4 (Chapter 5): Fostering students' mechanistic reasoning in physics: Learning by constructing stop-motion animations

The general aim in this fourth study was to explore the implementation of SMA construction activities as a learning approach in a classroom setting that supports students' MR. In this study, a lesson was set up in ways that students worked collaboratively in constructing an SMA model of electrostatics phenomena. Student-generated SMAs were then analyzed to find out the conditions under which the creation of SMA contributes to developing students' MR. The findings showed that students' development of MR was associated with the quality of SMA as judged according to a certain design, i.e., (1) the sequence from one chunk to the next in an SMA represents the change in a state at microscopic levels, and (2) an SMA provides the explicit description of the transition between these chunks with the intention to specify why and how the change happens.

General conclusions

Our review study showed that MR is an essential aspect of science education, but developing MR is challenging for students. One of the ways to support students in developing MR is to ask them to construct and use a model to reason. Our studies have shown theoretically and empirically that the nature of SMA construction, i.e., chunking and sequencing, played a crucial role in supporting students in developing MR. As a theoretical perspective, our framework depicts that constructing SMA by chunking and sequencing, which serve as modeling and a cognitive tool, promotes the elements of MR. This framework was confirmed by empirical findings showing that students developed MR when engaging in chunking and sequencing. Based on the findings, our studies suggest practical implications regarding what to consider when implementing SMA construction activities in a science classroom to support students' MR, and implications for future research to gain a more comprehensive understanding of the implementation of SMAs-based modeling in science classrooms that supports students in developing MR, in particular, and in science learning, in general.

Samenvatting

Wetenschappelijke geletterdheid is één van de doelen van ons bètaonderwijs. Bij leerlingen in het voortgezet onderwijs kan deze wetenschappelijke geletterdheid worden bevorderd door hen in contact te brengen met -voor zover mogelijk- realistische situaties in de wetenschapspraktijk en met wetenschappelijk redeneren. Mechanistisch redeneren (MR) is een vorm van causaal redeneren die essentieel is om wetenschappelijke verklaringen te construeren. MR wordt daarom beschouwd als een voorbeeld van wetenschappelijk redeneren. Het ontwikkelen van MR blijkt echter moeilijk voor leerlingen. Om hen te ondersteunen bij dit proces, lieten we in deze reeks studies leerlingen een model construeren om dat vervolgens te gebruiken om hun redenering rondom een bepaald fenomeen te ondersteunen. De modellen die leerlingen maakten waren zogenaamde *stop-motion animations* (SMA's). Dit proefschift beschrijft vier onderzoeken die werden uitgevoerd om de overkoepelende onderzoeksvraag te beantwoorden:

> *Hoe kunnen door leerlingen geconstrueerde SMA's worden gebruikt als een instructiemethode om leerlingen te ondersteunen bij het ontwikkelen van MR?*

De verschillende studies worden hieronder kort toegelicht.

Studie 1 (Hoofdstuk 2). Mechanistisch redeneren in het bètaonderwijs: Een literatuuroverzicht

Verschillende studies hebben mechanistisch redeneren (MR) in het onderwijs in de bètavakken onderzocht en een systematische synthese van dit werk is gewenst. Daarom hebben we een literatuurstudie uitgevoerd om te achterhalen wat er in onderzoek bekend is over MR in het bètaonderwijs. Uit de bestudeerde literatuur bleek dat MR gezien kan worden als een vorm van causaal redeneren die gekenmerkt wordt door twee basiselementen, namelijk entiteiten en activiteiten van die entiteiten. De bevindingen laten zien dat het identificeren van entiteiten en het specificeren van activiteiten van entiteiten de moeilijkste problemen zijn voor leerlingen bij het ontwikkelen van MR. Er werden in de literatuur verschillende strategieën genoemd om leerlingen te ondersteunen bij het ontwikkelen van MR. Eén van deze strategieën laat leerlingen een model maken om dit vervolgens te gebruiken bij hun redeneringen.

Studie 2 (Hoofdstuk 3). Stimuleren van mechanistisch redeneren in de natuurkunde met door leerlingen gemaakte stop-motion animaties

De tweede studie had als doel om uit te zoeken of (en hoe) het construeren door de leerlingen van een SMA-model van de beweging van een voetbal hun MR daarover beïnvloedde. De bevindingen toonden aan dat alle leerlingen als model van deze beweging een SMA konden construeren dat leek op een gebogen baan. Toen leerlingen hun eigen SMA gebruikten om te redeneren over de beweging van de bal, lieten ze MR zien, wat bleek uit het feit dat de basiselementen van MR (d.w.z. entiteiten en activiteiten van entiteiten) werden gebruikt. Bovendien bleek het abstracte denken van de leerlingen zich te ontwikkelen.

Studie 3 (Hoofdstuk 4). Begrijpen hoe door leerlingen gemaakte stop-motion animaties mechanistisch redeneren bevorderen: Een theoretisch kader en empirische onderbouwing

Deze studie onderzocht hoe de constructie van SMA's MR bevordert. Er werd een theoretisch kader ontwikkeld om de aard van de constructie van SMA's, d.w.z. het in stukken verdelen en die stukken in een volgorde plaatsen (het zogenaamde chunking en sequencing), te koppelen aan de zeven elementen van MR die Russ et al. (2008) eerder hadden geïntroduceerd. Om te onderzoeken in hoeverre het raamwerk in de praktijk functioneert, werd een meervoudige casestudie uitgevoerd waarbij leerlingen een SMA van elektrostatische verschijnselen construeerden. De resultaten bevestigden het raamwerk door aan te tonen dat alle leerlingen entiteiten en activiteiten van entiteiten gingen identificeren toen ze bezig waren met *chunking* en sequencing tijdens het maken van de SMA. *Chunking* speelde een rol bij het faciliteren van leerlingen om entiteiten te identificeren die verantwoordelijk zijn voor elektrostatische verschijnselen, en *sequencing* leek leerlingen te stimuleren om activiteiten van die entiteiten te specificeren om uit te leggen waarom en hoe deze verschijnselen optreden.

Studie 4 (Hoofdstuk 5). Het mechanistisch redeneren van leerlingen in natuurkunde bevorderen: Leren door stop-motion animaties te maken

De vierde studie onderzocht de praktische implementatie van SMA als een didactische aanpak met als doel de MR van leerlingen te ondersteunen. In deze studie werd een les ontworpen waarbij leerlingen samenwerkten bij het construeren van een SMA-model van elektrostatische verschijnselen. De SMA's die leerlingen maakten werden vervolgens geanalyseerd om zo de voorwaarden te achterhalen waaronder het maken van SMA's bijdraagt aan de ontwikkeling van MR bij de leerlingen. De bevindingen toonden aan dat de mate van ontwikkeling van MR bij leerlingen samenhangt met de kwaliteit van de gemaakte SMA's. Deze kwaliteit komt tot uiting in twee kernaspecten: (1) de mate waarin de volgorde van de *chunks* in de SMA correspondeert met de verandering van toestanden op microscopisch niveau, en (2) de mate waarin de overgang tussen de verschillende *chunks* het hoe en waarom van de verandering expliciet beschrijft.

Algemene conclusies

Onze studies toonden aan dat het ontwikkelen van MR essentieel is in het bètaonderwijs, maar dat het ontwikkelen van MR een uitdaging is voor leerlingen. Eén van de manieren om leerlingen te ondersteunen bij het ontwikkelen van MR is hen te vragen een model te construeren en dat vervolgens te gebruiken om te redeneren. Onze studies hebben theoretisch en empirisch aangetoond dat de specifieke aard van de constructie van SMA's, d.w.z. *chunking* en *sequencing*, een cruciale rol kan spelen in de ondersteuning van leerlingen bij het ontwikkelen van MR. Ons theoretische raamwerk laat zien dat het construeren van een SMA als model en cognitief hulpmiddel, via het proces van *chunking* en *sequencing* de elementen van MR naar voren brengt. Dit raamwerk is bevestigd door de resultaten die aantoonden dat leerlingen MR ontwikkelden toen ze bezig waren met *chunking* en *sequencing*. Op basis van de bevindingen suggereren onze studies praktische implicaties met betrekking tot het implementeren van SMA-constructieactiviteiten in lessen in de bètavakkken om daarbij de ontwikkeling van MR bij leerlingen te ondersteunen.

Ringkasan

Literasi saintifik adalah salah satu tujuan dalam pendidikan sains. Literasi saintifik siswa dapat dibangun dengan melibatkan siswa dalam praktik-praktik sains, yang salah satunya adalah membangun penjalasan secara ilmiah. Penalaran mekanistik (MR) merupakan salah satu bentuk penalaran kausal yang sangat penting untuk membangun penjelsan ilmiah. Oleh karena itu, MR dianggap sebagai contoh penelaran ilmiah. Namun, bernalar secara mekanistik (MR) terbukti tidak mudah bagi siswa. Untuk membantu siswa dalam mengembangkan MR, kami melaksanakan serangkain penelitian yang meminta siswa untuk membuat model berbasis animasi stop-motion (SMA) dan kemudian menggunakan model tersebut untuk menjelaskan fenomena fisika.

Bab ringkasan ini mendeskripsikan keempat penelitian yang telah dilaksanakan untuk menjawab pertanyaan utama penelitian:

> *Bagaimana aktivitas siswa membuat SMA dapat digunakan sebagai strategi pembelajaran untuk membantu siswa mengembangkan MR?*

Penelitian ke 1 (Bab 2): Penalaran mekanistik dalam pendidikan sains: Sebuah tinjuan literature

Penelitian pertama bertujuan untuk meninjau penelitian-penelitian tentang MR dalam topik pendidikan sains untuk mencari tahu bagaimana penelitian-penelitian tersebut mengkonsepkan MR dan temuan utamanya. Temuan di tinjauan literatur ini menunjukkan bahwa MR dianggap sebagai penalaran kausal yang dicirikan oleh dua elemen dasar, yaitu *entities* dan *activities of entities*. Kami juga menemukan bahwa kesulitan utama siswa dalam bernalar secara mekanistik adalah mengindetifikasi *entities* dan menentukan *activities of entities*. Tinjuan literatur kami menunjukkan berbagai bentuk strategi untuk membantu siswa mengembangkan penalaran mekanistik mereka. Salah satu strategi ini adalah meminta siswa untuk membuat model suatu sistem atau fenomena alam untuk kemudian digunakan untuk bernalar tentang sistem atau fenomena tersebut.

Penelitian ke 2 (Bab 3): Menstimulasi penalaran mekanistik pada topik fisika melalui animasi stop-motion yang dibuat oleh siswa

Di penelitian kedua kami bertujuan untuk mengetahui (dan bagaimana) animasi stop-motion (SMA) yang dibuat siswa untuk memodelkan gerak bola menstimulasi siswa bernalar secara mekanistik saat menjelaskan gerak bola tersebut. Hasil penelitian menunjukkan bahwa seluruh siswa yang berpartisipasi di penelitian ini membuat SMA untuk memvisualisasikan gerak bola yang menyerupai lintasan melengkung. Siswa menggunakan penalaran mekanistik (MR), yang dibuktikan dengan penggunaan *entities* dan *activities of entities* dalam penalarannya, ketika menggunakan animasinya untuk menjelaskan bentuk gerak bola ini. Salain itu, penalaran yang menggunakan konsep abstrak tampak berkembang.

Penelitian ke 3 (Bab 4): Memahami bagaimana animasi stop-motion yang dibangun siswa mendorong penalaran mekanistik: Sebuah gagasan teoritis dan bukti empiris

Penelitian ketiga ini bertujuan untuk menyelidiki bagaimana animasi stop-motion (SMA) yang dibuat siswa mendorong penalaran mekanistik (MR). Kami mengusulkan sebuah gagasan teoritis untuk menghubungkan karakteristik SMA (yang disebut *chunking and sequencing*) dengan tujuh elemen-elemen dari MR yang diperkenalkan oleh Russ et al. (2008). Untuk menginvestigasi apakah gagasan teoritis ini terbukti secara empiris, sebuah studi kasus dilakukan dengan melibatkan siswa yang membuat sebuah SMA tentang fenomena eletrostatik. Hasil penelitian mengonfirmasi gagasan teoritis kami dengan memperlihatkan bukti bahwa semua siswa mengindentifikasi *entities* dan menentukan *activities of entities* ketika mereka terlibat *chunking* dan *sequencing* (proses membuat SMA). *Chunking* berperan dalam memfasilitasi siswa untuk mengidentifikasi entities yang berhubungan dengan fenomena elektrostatis, sedangkan *sequencing* nampak menstimulasi siswa untuk menentukan *activities of entities* yang berkaitan untuk menjelaskan mengapa dan bagaimana fenomena eletrostatis terjadi.

Penelitian ke 4 (Bab 5): Mendorong penalaran mekanistik siswa dalam topik fisika: Pembelajaran dengan membuat animasi stop-motion

Penelitian keempat ini bertujuan untuk mengeksplorasi implementasi sebuah rancangan pembelajaran fisika di kelas yang menggunakan sebuah bentuk strategi pembelajaran yang meminta siswa secara berkelompok untuk membuat animasi stop-motion (SMA) yang memvisualisasikan model tentang fenomena elektrostatis. Kami menelaah SMA yang telah dibuat siswa dianalisa untuk memahami sejauh mana SMA tersebut berpengaruh terhadap penalaran mekanistik (MR) siswa. Hasil penelitian menunjukkan bahwa kualitas SMA berhubungan dengan MR siswa. Kualitas SMA ini mengandung dua aspek, yaitu: (1) sebuah SMA memuat *chunks* yang memvisualisasikan suatu perubahan keadaan di tingkat mikroskopis, dan (2) sebuah SMA memuat penjelasan secara eksplisit tentang transisi antara *chunks* ini yang menjelaskan mengapa dan bagaimana perubahan tersebut terjadi.

Kesimpulan

Hasil penelitian menunjukkan bahwa penalaran mekanistik (MR) merupakan aspek yang penting di pendidikan sains, tetapi siswa menghadapi kesulitan dalam mengembangkan MR-nya. Salah satu cara untuk membantu siswa mengembangkan MR-nya adalah dengan menugaskan siswa untuk membuat model dan kemudian menggunakannya untuk bernalar. Penelitian kami telah memberikan gagasan teoritis dan menujukkan bukti empiris bahwa karakteristik SMA, yaitu *chunking* dan *sequencing*, berperan penting dalam mengembangkan MR siswa. Gagasan teoritis kami menjelaskan bahwa proses membuat SMA dengan proses *chunking* dan *sequencing* menganggap sebagai pemodelan dan *cognitive tools* dan proses ini dapat memunculkan elemen-elemen MR. Bukti empiris mengonfirmasi gagasan teoritis ini dengan menunjukkan bahwa siswa membangun MR ketika mereka terlibat dalam proses *chunking* dan *sequencing*. Temuan di penelitian kami berimplikasi pada implementasi aktivitas siswa membuat SMA sebagai bentuk strategi pembelajaran yang dapat mendorong dan mengembangkan MR pada siswa.

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Biography

Rayendra Wahyu Bachtiar was born on January 19th, 1989, in Banyuwangi, East Java, Indonesia. He is the second child of two siblings. His parents (mother and father) worked as teachers in a primary school in Tapanrejo, one of the villages in Banyuwangi.

After graduating from SMAN 1 Genteng, a senior high school, in 2006, he continued his studies at the university and received a Bachelor’s degree in physics education from Malang State University, Indonesia, in 2010. He then took a master’s degree in physics education at the same university and graduated in 2012.

In addition to his work as a (either bachelor or master) student in the university, he actively became a physics tutor to secondary school students. While pursuing his master’s degree, he also worked as a physics teacher at SMAN 5 Malang, a senior high school. In 2011, together with his two friends, he built a start-up company focused on education, e.g., providing tutoring services to students. This business grew significantly within 2 years. However, due to some circumstances, he and the other two founders decided to cease operations of the company in 2013.

In 2013, through a national selection process, he was accepted as a staff member at the Department of Physics Education, Faculty of Teacher Training and Education, at University of Jember, Indonesia. In this department, he was appointed as a lecturer and a researcher in charge of some academic activities, such as providing courses for pre-service physics teachers, providing workshops for science teachers, and managing and conducting (together with his bachelor students) research in the field of physics education.

In 2018, he got a grant from 4IN1 project (Islamic Development Bank) IsDB project-DIKTI Indonesia, which allowed him to pursue PhD program. In March, 2018, he started a PhD project under the supervision of Prof. Wouter van Joolingen and Dr. Ralph Meulenbroeks, at Freudenthal Institute, Utrecht University, Netherlands. His PhD research project focused on: mechanistic reasoning in physics as a learning goal and modeling with stop-motion animations as a learning approach.

Together with his wife and his daughter, he lived in Utrecht for two years. On December 21st, 2019, his son was born. Near the end of 2020, he and his family moved to Wassenaar.

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Mechanistic reasoning (MR), which is a form of causal reasoning, is an essential aspect of science education. To support students in developing MR, students in this series of studies were tasked with constructing and using a model in the form of a stop-motion animation (SMA). In SMA students create a sequence of frames (images) representing a natural phenomenon. After creating the SMA, they were asked to explain the phenomenon on the basis of their own model.
This dissertation describes four separate studies that were conducted to address the main research question: How can student-constructed SMAs be used as a pedagogical approach to support students in developing MR? Our studies show, both theoretically and empirically, that the specific nature of SMA construction, i.e., breaking up a natural phenomenon in chunks and then sequencing these chunks in order to create the SMA, played a crucial role as a cognitive support for students in developing key elements of MR. Based on the findings, our studies suggest practical implications regarding for implementing SMA construction activities in a science classroom to support students' MR. The results contribute to a more comprehensive understanding of the implementation of SMA-based modeling in science classrooms that supports students in developing MR, in particular, and in science learning, in general.

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