

Article

Describing Mechanisms in COVID-19 Media Coverage: Insights for Science Education

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Abstract

Public media serves as a significant source of scientific information for non-scientists. However, the simplifications and omissions inherent in media reporting often alter the nature of scientific information, potentially influencing understanding and perceptions of science and the nature of science. This study investigates how mechanistic explanations about biological processes are represented in public media, focusing on two forms of incomplete mechanistic information: “gray boxes” and “black boxes”. Using COVID-19 as a case study, we analyzed 122 media reports of biological mechanisms to understand how incomplete parts are masked by more complete explanations and their implications. Our findings highlighted three main points. First, incomplete information often appears alongside complete information within other parts of the explanation. Second, some parts of similar mechanisms are presented differently, which can create a sense of conflicting information if incompleteness is not recognized. Third, multiple filler terms are used to mask black boxes within biological explanations (e.g., “cause”, “fight”, or “mutate”). While filler terms enhance narrative flow, they can obscure gaps in scientific knowledge and lead to anthropocentric or teleological explanations. We categorized these filler terms into three groups and discussed their relevance to teaching and learning. Implications for addressing partial information in the science classroom are discussed.



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1. Introduction

Public media is one of the primary sources of scientific information that is accessible to the general public. While scientific articles are more accurate and reliable, they are often challenging to understand and less accessible to non-experts (e.g., [Duncan et al., 2018](#); [Feinstein, 2014](#)). Even in schools, teachers frequently rely on media reports to introduce students to recent scientific advancements ([Gardner et al., 2009](#); [Nettlefold & Williams, 2021](#); [Madhuri & Broussard, 2008](#); [Tsai et al., 2013](#)). For example, a study conducted in Australia found that out of 97 teachers, 90 reported engaging students with news stories, with 18 of them indicating that they do so very often ([Nettlefold & Williams, 2021](#)). [Höttecke and Allchin \(2020\)](#) proposed that understanding how scientific knowledge is transformed through public media communication could improve its practical use. They claimed that although they transform, scientific claims can retain their integrity and reliability as they move from science to the public. However, little research has been conducted on the nature of these transformations, particularly their potential impact on individuals’ understanding, trust, or perception of science.

Some studies indicate that these transformations result in more simplified and incomplete information (Brechman et al., 2009; Davis & Russ, 2015; Guenther et al., 2019; Van Atteveldt et al., 2014). For example, a study that analyzed news stories reporting on cancer-related genetics research found a tendency toward overgeneralization, biological determinism, and information simplification (Brechman et al., 2009). Another study investigating the representation of scientific uncertainty in German print and online media articles revealed that scientific results are often portrayed as certain, and the criteria for assessing scientific evidence and references of uncertainty are mostly omitted (Guenther et al., 2019). Furthermore, a study of media publications addressing neuroscience research revealed that articles in popular newspapers offered minimal detail (Van Atteveldt et al., 2014).

The differences between the scientific publication and the resulting media report reflect a shift in how science is presented: from complex to simple and deterministic, and from uncertain to certain. Such representations may cause confusion about scientific concepts as well as about the nature of science. Consequently, it has been argued that learning about the nature of science should include understanding how it is communicated, particularly when selective simplification occurs. This approach can help students not only grasp scientific concepts but also appreciate how these concepts are adapted across different contexts (Höttecke & Allchin, 2020). Such understanding can reduce the risk of generating a sense of contradiction or causing confusion about scientific concepts. Achieving this requires a more detailed characterization of how information changes in media representations. For instance, we need to examine more closely how scientific concepts and processes are presented in different media reports, how they are simplified, and how they become deterministic.

This is not an easy task because there are many different types of information (e.g., experimental reports, data, explanations), each of which may be characterized differently. Hence, in this study, we focused on a specific type of information: mechanistic explanations. Mechanistic explanations are central in science because they are used to explain, predict, and control natural phenomena (Craver & Darden, 2013; Machamer et al., 2000). Such explanations include a specific arrangement of entities and activities that can link cause to effect (Craver & Darden, 2013; Glennan & Illari, 2017).

Mechanistic information has been shown to assist laypeople in drawing causal inferences and in having confidence in a suggested causal connection (Ahn & Kalish, 2000; Koslowski, 1996). Due to their essential role in linking cause and effect, the importance of teaching and learning mechanisms was acknowledged in science education. Research in the field focused on students' understanding of scientific mechanisms and the processes of reasoning about mechanisms (e.g., Bachtiar et al., 2022; Russ et al., 2008; Tang et al., 2020). Some of the identified challenges in understanding scientific mechanisms are related to their complexity.

Scientific mechanisms are complex, particularly in multileveled domains such as biology. In biology, mechanistic explanations often delve into deeper levels of organization and involve multiple components, interactions, and feedback loops (Baetu, 2015; Craver & Darden, 2013). To help students understand these mechanisms, they are simplified in biology classrooms by omitting mechanistic details. However, educators strive to ensure that students recognize these simplifications, preventing overly simplistic or deterministic views and laying the groundwork for mastering more complex ideas in the future (Barreto et al., 2021; Jiménez-Aleixandre, 2014; Livni Alcasid & Haskel-Ittah, 2024; Mouton & Archer, 2019).

An example of the ongoing discussion around the careful simplification of scientific information arises in the context of genetics. Several studies addressed the challenge of helping students understand the complex and indirect relationship between genes

and traits without delving into all the details of the mechanisms that link them (Burian & Kampourakis, 2013; Donovan, 2016; Haskel-Ittah, 2021; Jiménez-Aleixandre, 2014). Another example involves understanding the cell membrane as both a barrier separating the cell from its environment and a facilitator of material transport. Research has shown that this concept is presented with varying levels of specificity and complexity at the high school and university levels, and students often face significant challenges during these transitions (Mouton & Archer, 2019).

Consequently, it has been argued that students should understand that scientific descriptions may vary over time for two key reasons: science evolves as new evidence emerges, and descriptions inherently focus on specific aspects of nature, shaped by their communicative purposes (Ryan et al., 2023). Recognizing these factors is considered part of a broader understanding of the nature of science, including its communicative dimensions (Allchin, 2022).

To help students identify informational changes or differing descriptions of similar mechanisms in media reports, understand their communicative purposes, and avoid confusion about biological concepts, it is essential first to develop a clearer understanding of how such information is presented in the media.

In this study, we aimed to characterize how information about three biological mechanisms (viral infection, variant formation, and vaccination mechanisms) in the context of COVID-19 is presented in public media. We utilized a lens of incompleteness to analyze how various media reports explain similar or related mechanisms. In the following section, we will elaborate on the lens of incompleteness and its connection to conceptual understanding, the nature of science, and how it is communicated.

Theoretical Framework

When addressing incomplete mechanistic information, we must first define the components of a mechanistic explanation. In science education, several components of mechanistic explanations have been characterized based on the philosophy of science. They include entities with specific properties, their activities or functions, and their organization in space and time (Russ et al., 2008). In addition, Krist et al. (2019) proposed that the explanation includes a causal link of all components from cause to effect. Information containing a complete mechanistic explanation should thus include all entities along with their functions, properties, and organization; however, such information rarely exists and would encompass a wealth of details that might be irrelevant, even for a computer modeling the mechanism, let alone for a human being trying to make sense of it (Craver & Kaplan, 2020; Machamer et al., 2000). Craver and Darden (2013) thus suggested that because not all mechanistic details are relevant or known, some should be excluded because their exclusion depends on the aim of the information and the audience. Different types of missing details should be characterized when aiming to address incompleteness.

One type of missing detail is scientific terminology. For example, the MAP-kinase enzyme can be described as a protein kinase or merely as an enzyme, or the hormone insulin may be described as a hormone without specifying its name. This type of missing detail does not make the information mechanistically incomplete; this is because, based on the definition above, the scientific name of an entity is not considered part of its properties as long as it is identified by a name that distinguishes it from other entities in the mechanism. In contrast, the organization of the entity in space and time and its structure are details that, if missing, make the information incomplete in terms of the entity's characterization.

Since entities and their functions are the core components of the mechanism, describing an entity without a function or a function without an acting entity is considered an incompleteness that has been termed a “gray box” (Craver & Darden, 2013). An example of such gray box information might be a description of insulin as secreted and binding to the receptor without specifying the entity involved in the secretion function.

Even greater incompleteness may occur when both the entity and activity, or even a small chain of entities and activities, are missing. These gaps have been termed “black boxes” (Craver & Darden, 2013; Haskel-Ittah, 2023; Keil, 2019). These black boxes are not just missing details but parts of the mechanism with a known relationship between cause and effect. However, the specifics of *how* this relationship, which occurs through interactions between entities, is not detailed. These black boxes can appear as the following:

Implicit black boxes are where a certain part of a mechanism is masked by filler terms, for example, “cause”, “lead to”, or “produces”. Filler terms represent black box causal relationships (Craver & Darden, 2013); they are often used to indicate a type of activity in a mechanism without providing any details of how that activity is executed, for example, “the virus enters the cell, and the cell produces more viruses”.

Hidden black boxes are where a process is skipped and is absent from the explanation. Instead, two parts of a mechanism are linked by a conjunction; for example, an explanation of a viral infection hiding the mechanism of virus replication would be “the virus enters the cell, and then there are many viruses in the cell”.

In this study, we focused on the three robust types of information incompleteness: gray boxes, implicit black boxes, and hidden black boxes, to explore the completeness of the mechanistic structures of mechanistic information in the media.

Both gray boxes and black boxes represent the nature of science as well as how science is communicated. Scientific knowledge constantly evolves, often uncovering new roles for known entities (gray boxes) or revealing mechanisms behind processes that were previously understood to occur without clarity on how they worked (black boxes). These evolving insights highlight a crucial aspect of science’s dynamic and tentative nature, particularly in emerging scientific fields or during health crises, such as the COVID-19 pandemic. Such gray or black boxes provide an opportunity to observe this dynamic, as long as they are represented in a way that clearly highlights the unknowns. However, in this study, we could not find such highlighting of information that is unknown to science, and thus, we will not focus on this aspect.

Gray and black boxes reflect an epistemic dimension of science, emphasizing how scientific knowledge is communicated. In educational curricula, communication usually evolves systematically, becoming progressively more complex at higher levels of study (Barreto et al., 2021; Mouton & Archer, 2019). In contrast, media representations of science may vary based on the explanation’s context, target audience, and purpose rather than following a linear progression.

Understanding why certain parts of an explanation are presented as black or gray boxes while others are elaborated upon is essential for appreciating the variability in scientific communication. These variations reflect differences in focus or purpose, as well as choices between simplifying or presenting complexity. Such distinctions highlight the selective emphasis that is inherent in scientific explanations.

However, if these gray or black boxes are not explicitly identified as incomplete, confusion about scientific concepts or doubts about the reliability of the information may occur. Explanations that describe the same mechanism differently may mistakenly appear to be conflicting, further contributing to misunderstandings.

The risk is heightened when some parts of an explanation are detailed while others remain incomplete, as the detailed sections can mask the gaps, making all parts appear to be equally well-established.

In this study, we aimed to investigate how gray boxes and black boxes appear in media representations of different biological mechanisms. Specifically, we explored whether incomplete sections are masked by more complete parts of the explanation, how and why they are masked, and whether they give rise to biological conceptions that may conflict with one another or prior school learning. By examining these aspects, we sought to better understand how incomplete mechanistic information influences the communication of scientific information.

Therefore, our research questions included the following:

How are different biological mechanisms presented in public media, specifically in terms of the representation of gray boxes, black boxes, and more complete sections of explanation?

How do filler terms in public media contribute to masking the presence of biological black boxes?

Our study specifically targeted COVID-19-related mechanisms due to the tremendous amount of information available in the media and the multiple biological contexts related to the pandemic (immune system, evolution, molecular biology, and more).

2. Methodology

2.1. Data Collection

To characterize the incompleteness of the information on COVID-19-related mechanisms in the media, we used document analysis. Through qualitative content analysis, document analysis involves the skimming, close reading, and interpretation of texts, producing relevant excerpts that are grouped into themes and categories (Bowen, 2009). In this study, the pertinent documents were media reports about biological mechanisms related to COVID-19.

To investigate potential differences in the completeness of explanations across various biological contexts, we focused on three COVID-19-related mechanisms: infection, variant formation, and vaccination. These selected mechanisms encompassed distinct biological contexts: microbiology, evolution, and immunology, respectively.

We collected media reports by searching for questions or keywords in Google, such as “How does the coronavirus infect the human body?” or “coronavirus variant”. We searched for the questions/keywords in both English and [another language blanked for review]. The first 20 Google search results for each question or keyword were collected. The searches were conducted in “Incognito” search mode and were performed from various computers to ensure a diverse range of information sources. Each Google result that was openly accessible to the public was considered as a media report. Some data were collected in March 2021, and the rest were collected one year later to verify that there was no effect of the period in which the reports were published on the mechanistic explanation.

In total, 122 reports were collected and analyzed (43 media reports on the variant formation mechanism, 38 on the infection mechanism, and 41 on the vaccination mechanism). The collected reports were obtained from multiple national and international popular science news websites (e.g., Scientific American, Washington post), medical or government websites (e.g., Modern Healthcare, the Australian government, the WHO), and academic websites (e.g., Harvard Health Publishing, MIT). A list with all sources of media reports can be found in the Supplementary Materials. Due to the substantial similarity in phrasing among articles from various websites, we assumed that they were not fully independent

but rather relied on one another. As a result, we did not perform a comparative analysis across sources. Nonetheless, this diverse range of media types allowed us to observe how explanations are expressed across platforms targeting different audiences and serving various purposes.

2.2. Data Analysis

All media reports were uploaded to Atlas.ti software (Version 23.0.6).

In biology, mechanistic explanations can span the molecular level to the organismal level, or even the level of ecological systems. Thus, to characterize an explanation's completeness, we had to define the borders of each explanation in terms of the core processes it includes. In the first step, we used a bottom-up analysis to divide each mechanism into three main sub-mechanisms, representing the processes emphasized in the collected media reports (Figure 1). These three sub-mechanisms were present in all media reports but were described with varying levels of completeness.

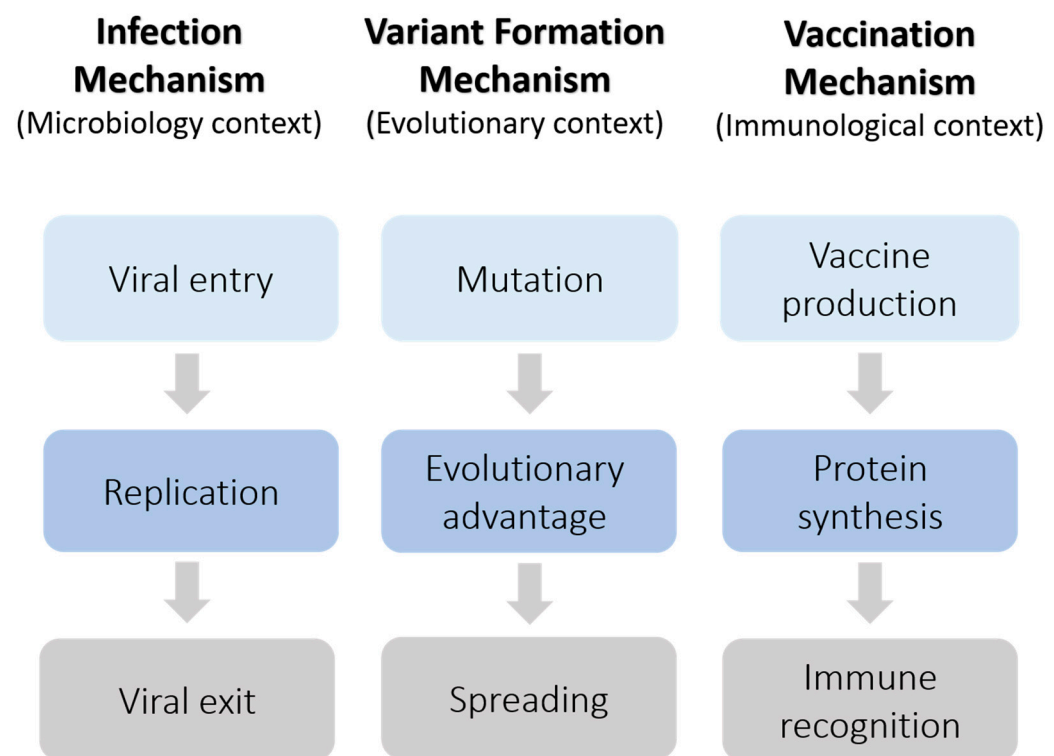


Figure 1. Subdivision of mechanisms into processes (sub-mechanisms).

To evaluate this level of completeness, specific input and output were first defined for each sub-mechanism. For example, the input for the sub-mechanism “viral entry” was an external virus and the output was the content of the virus inside the cell. The sub-mechanism included information about the process linking the input and output. We examined the existence of functioning entities that are part of the sub-mechanism linking the input to the output (Krist et al., 2019; Russ et al., 2008). Of course, what counts as unpacking for lay individuals may still appear as black boxing to experts capable of deeper analysis. Therefore, by delineating three sub-mechanisms for each phenomenon, each aligned with core ideas from biology curricula and standards (e.g., NGSS Lead States, 2013; UK Department for Education, 2014), we specified the phenomena under consideration, identified the constituent processes of each, and defined the most basic level of detail that qualifies as unpacking (at least one functioning entity linking the input to the output).

After establishing the borders of each sub-mechanism, we defined the level of completeness for each. This was performed as follows: In cases where the sub-mechanism was absent or only its input and output existed, it was coded as a black box. Cases in which information about at least one functioning entity linked the input and output were coded as complete. However, if one or more described entities were described without their functions, or functions were described without their entities, the sub-mechanism was coded as a gray box (Table 1). These three mechanistic structures of sub-mechanisms—complete, black box, or gray box—represented the possible combinations for each mechanism (e.g., *black box, complete, complete, or gray box, gray box, gray box*).

It should be emphasized that according to this coding scheme, complete sub-mechanisms are not complete in the sense that they include all involved entities and activities. As explained in the Introduction section, this completeness rarely appears. These sub-mechanisms are complete in the sense that they provide some information about functioning entities in the mechanism (not a black box sub-mechanism) and do not leave entities without their function or functions without entities (not a gray box). Accordingly, a complete mechanism is a mechanism in which all three sub-mechanisms were coded as complete, and incomplete mechanisms may include different combinations of complete and incomplete sub-mechanisms.

Table 1. Mechanistic structures classified into types, with examples.

Mechanistic Structure	Example	Explanation for Coding
Black box	<i>"The virus produces more viruses in the cell"</i> (sub-mechanism: replication)	The explanation does not include information about the sub-mechanism; it includes the filler term "produces", which masks the replication mechanism
Complete sub-mechanism	<i>"To produce an mRNA vaccine, scientists create a synthetic version of mRNA encoding the spike protein. This is packaged inside fatty parcels, to make it easier for the mRNA to cross the outer membranes of cells"</i> (sub-mechanism: vaccine production)	The explanation includes an additional entity (spike protein) and activity (membrane crossing) that link the input (RNA vaccine is synthesized) to the output (RNA vaccine inside the cell)
Gray box	<i>"The immune system responds by developing longer-lasting immunity in the form of T cells and B cells"</i> (sub-mechanism: immune recognition) <i>"Inside the host cell, they [the viruses] use its genetic material to reproduce"</i> (sub-mechanism: replication)	The explanation does not specify the functions of T cells and B cells Although there is another entity, "genetic material", the explanation does not specify the entity responsible for the act of replication

Each sub-mechanism was also analyzed and coded according to its biological content. For example, in a media report regarding the infection mechanism, the viral entry sub-mechanism was assigned two codes: one for the biological content (viral entry) and another for the type of mechanistic structure (complete/gray box/black box).

To answer the second research question, identified black boxes were further analyzed. They were categorized into hidden (omitted sub-mechanism) and implied black boxes (sub-mechanisms masked by a filler term). Filler terms were collected and categorized bottom-up into different groups, as elaborated in the Results section.

To ensure the validity and reliability of the coding, two researchers coded 25% of the data independently. An 83% inter-rater agreement was achieved after an iterative process that included code refinement, and complete agreement (100%) was achieved on the codes.

3. Results

In this study, we investigated how gray boxes and black boxes appear in media representations of COVID-19-related mechanisms. Specifically, we explored whether incomplete sections are masked by more complete parts of the explanation and how they are masked in different biological mechanistic contexts—microbiology (the infection mechanism), evolution (the variant formation mechanism), and immunology (the vaccination mechanism).

We first present our findings as related to each mechanistic context as a whole (infection, variant formation, and the vaccination mechanisms) and then delve into the analysis of specific parts (sub-mechanisms) that constitute each mechanistic context.

3.1. Completeness and Incompleteness in Specific Biological Contexts

In the three different biological mechanistic contexts—infection, variant formation, and vaccination mechanisms—we found that mechanisms often contain a mix of complete and incomplete parts. Only 12 out of 122 media reports included mechanisms where all three analyzed sub-mechanisms were complete. This finding highlights that most mechanisms in the media are not fully complete; instead, they blend complete and incomplete sections.

It is important to clarify that when we describe sub-mechanisms as complete, we do not mean that they include all possible entities and activities. Rather, these sub-mechanisms are considered complete because they provide information about some functioning entities within the mechanism (i.e., no black box sub-mechanisms) and that no entities lack a function and no functions lack corresponding entities (i.e., no gray boxes). Completeness, in this sense, means that the sub-mechanisms avoid potential confusion by not leaving parts unlinked or masking incomplete sections beneath seemingly complete ones.

The mixture of complete and incomplete parts can obscure the recognition of incomplete ones. This uneven distribution of completeness differed between biological contexts. Thus, we present the distribution separately for each context to better understand how these mixtures are structured and how they might influence comprehension.

I. Infection mechanism:

In the context of the infection mechanism, in total, most sub-mechanisms were classified as complete sub-mechanisms (43%, 49 out of 114, Table 2), while the least prevalent were gray box ones (24%, 27 out of 114, Table 2). The distribution into such proportions was significant (Table 2, $\chi^2 = 51.01$, $p < 0.01$). Namely, information from different media sources regarding COVID-19 infection may have a similar pattern of mostly complete sub-mechanisms, making connecting information about various parts of the mechanism easier.

The infection mechanism consists of three sub-mechanisms: viral entrance, viral replication, and viral exit. Viral entrance and viral exit mechanisms represent a central concept in biology that addresses the separation of cells from their external environment.

The viral entrance sub-mechanisms were mainly complete (68%, 26 out of 38, Table 2). These explanations included information about the entities and activities involved in the entrance of the virus into the cell, for example, a Spike protein, ACE2, and the cell membrane. On the contrary, the viral exit was mainly described in a black box manner. Seventy-six percent of the viral exit sub-mechanisms (29 out of 38) were of a black box type, hiding the mechanism explaining the exit of the virus from inside the cell. Some included implicit black box descriptions such as “and then the virus spreads in the body” or “then the viruses exit the cell”. Others completely omitted the sub-mechanism (hidden black box).

Table 2. The relationship between mechanisms/sub-mechanisms and the type of mechanistic structure in the analyzed media reports.

Mechanism	Sub-Mechanism	Black Box	Gray Box	Complete	Total	<i>p</i> -Value for Mechanism Chi-Squared Test
Infection	Viral entry	2	10	26	38	<0.01
	Replication	7	13	18		
	Viral exit	29	4	5		
	Total infection mechanism	38	27	49	114	
Vaccination	Vaccine production	15	13	13	41	<0.01
	Protein synthesis	24	8	9		
	Immune recognition	13	22	6		
	Total vaccination mechanism	52	43	28	123	
Variant Formation	Mutation	12	13	18	43	0.06
	Evolutionary advantage	10	5	28		
	Spreading	16	11	16		
	Total variant formation mechanism	38	29	62	129	

In the viral entry part, 26% (10 out of 38) of coded sub-mechanisms included gray boxes in which entities did not include an activity, for example, “The virus attaches itself to the cell membrane and enters it”. As an additional entity, the cell membrane has no function in such explanation, though it has a crucial role in separating cells from their external environment.

The viral replication sub-mechanism incorporates core ideas related to genetics and inheritance. Our analysis revealed that these sub-mechanisms were predominantly complete, with 47% providing detailed explanations that included information about RNA replication.

However, 34% of the replication sub-mechanisms contained gray box explanations, where key entities like “genetic material” or “DNA” were mentioned without any associated activities. Conversely, activities such as “make copies of the virus”, “duplicate”, or “create” were described without linking them to specific entities. For example, “From the moment it enters the cell, it injects a genetic cargo, RNA. Thus, it takes over the cell and directs it to produce more and more viruses instead of fulfilling its original function”. In this example, there is a combination of two gray boxes. First, there is the entity RNA, which appears in the explanation without being associated with any activity. Second is the activity “produce”, which appears without an entity performing it. This disconnect highlights gaps in how the replication process is presented.

II. Vaccination mechanism:

The vaccination mechanism encompasses processes that are relevant to core ideas about immunity. Most sub-mechanisms were classified as black box sub-mechanisms (42%, 52 out of 123, Table 2), while the least prevalent were complete sub-mechanisms (23%, 28 out of 123). This trend was also statistically significant (Table 2, $\chi^2 = 13.62$, $p < 0.01$), suggesting a consistent distribution across media sources of multiple gaps in explanations that may be challenging to bridge into a coherent understanding. This is highly important when such gaps appear in topics that are both relevant and highly difficult for students such as in immunology (Siani et al., 2024).

The vaccination mechanism comprises three sub-mechanisms: vaccine production (synthesis and injection), protein synthesis, and immune recognition. Vaccine production is more technical and less connected to core concepts in biology. In contrast, protein synthesis is a fundamental mechanism in genetics. Both sub-mechanisms were vaguely described by

the predominant use of black box structures (in 37%, 15 out of 41, and in 59%, 24 out of 41 of cases, respectively, Table 2). For example, “the mRNA enters the cells” or “the cells produce a protein”. From these examples, it can be seen that no other entities and activities clarified the causal link between mRNA outside the cells and mRNA inside the cells or the link between mRNA inside the cells and the production of viral proteins.

Most descriptions of the immune recognition mechanism (54%, 22 out of 41, Table 2) and some of the vaccine production mechanism (32%, 13 out of 41, Table 2) were gray boxes. For example, “our immune system responds by creating antibodies and developing long-lasting immunity in the form of T and B cells.” In this example of an immune recognition mechanism, the entities B cells and T cells appear without a defined function, forming a gray box.

III. Variant formation mechanism:

The context of the variant formation mechanism encompasses processes that are relevant to core ideas about evolution. In this context, most sub-mechanisms were classified as complete sub-mechanisms (48%, 62 out of 129, Table 2), while the least prevalent were gray box structures (22%, 29 out of 129, Table 2). However, the analysis revealed no significant relationship between the sub-mechanism and the type of mechanistic structure, meaning that information from different media sources may have different mechanistic representations.

The variant formation mechanism consists of three sub-mechanisms: mutation, evolutionary advantage, and spreading in the population. The mutation mechanism is highly related to core ideas in genetics and evolution and was predominantly described as complete (42%, 18 out of 43, Table 2) by providing information about the entities of nucleotides, which are similar to “words in a sentence” or “words in a book”. In other instances, it appeared as an implicit black box indicating that “the virus mutates” or “the virus’ DNA changes” without adding information about the mutation process.

The evolutionary advantage of this change was not always clearly described. In some cases, it was mentioned that “A random mutation can provide a virus with an ‘advantage’ that aids in its spread from person to person” or “The virus can spread more easily from person to person due to its mutations”. These examples lack an explanation of how the new variant gains an advantage. There is no clarification regarding the structural or property differences in the new variant that make it advantageous over the original virus. The final step of spreading in the population was described as either an implicit black box saying that “the virus has become more widespread” or as a complete mechanism explaining that “It does, however, spread faster than older variants and is rapidly becoming the most common variant in countries where it is present.”

3.2. Black Boxes and Filler Terms

Our findings showed that 128 (35%) of the analyzed sub-mechanisms (total of 366 sub-mechanisms) appearing in the media reports were black boxes. Of these, 88 (69%) were implicit black boxes, including a filler term. To better understand how filler terms mask these biological black boxes, we used a bottom-up approach to categorize the filler terms into two groups (see Table 3). One group comprised filler terms that did not specify the nature of the causal relationship, merely indicating that a relationship exists; 46% (41) of the filler terms were classified into this group, including “make”, “cause”, “develop”, and “activate”, for example, “*The vaccines develop immunity to disease*” or “*The virus becomes more widespread over generations.*” In these instances, one step in the sub-mechanism develops into or becomes the next. While this terminology implies that a masked mechanism is involved, it does not suggest *how* this change might happen.

The second group (54% of the filler terms) consisted of filler terms that provided additional information about the causal relationship and suggested a mechanism. Fur-

ther characterization of this group led to the identification of three types of filler terms: everyday-life analogies, analogies from different scientific domains, and biological terms. Analogies from everyday life included filler terms such as “fight”, “enter”, or “teach”. In these instances, the filler term suggests that the mechanism that is masked by the black box operates similarly to the mechanism underlying the analogy. For example, “*the immune system fights the virus*” suggests that the mechanism includes entities that are similar to soldiers. On other occasions, the analogies were from different scientific domains, such as “melt”, suggesting that the mechanism operates similarly to its operation in the melting mechanism.

Other filler terms that provided additional information used biological terms to specify the causal relationship, such as “mutate” or “infect”. In these instances, the filler term implied a biological mechanism that occurs at this step without clarifying how it actually works.

Table 3. Classification of filler terms.

Specified Nature of the Causal Relationship	Unspecified Nature of the Causal Relationship
enter or exit (including spread/leave/invade/burst)	Make (including create/produce)
duplicate	Cause
inject	Leads to
breaks open	trigger/activate
melt	become
leap	use
attack	Develop
build	
instruct	
fight	
mutate	
infect	
54% (47)	46% (41)

4. Discussion

4.1. Completeness of Mechanisms in Media Reports

Previous studies have shown that scientific information becomes simpler and deterministic when presented in the media (Brechman et al., 2009; Davis & Russ, 2015). This study explored this simplification by examining the structure of mechanistic information presented in media reports. Craver (2006) noted that even in science, most mechanisms lack a full description, making searching for complete completeness in media reports unreasonable. Thus, we established a different definition for a complete mechanism, i.e., a mechanism in which all three main sub-mechanisms include some information about functioning entities. Even with this much looser definition of completeness, we found that most media reports include a mix of complete and incomplete parts. In other words, the results suggest that scientific information is not only simplified in its presentation in the media but also contains gaps across the mechanistic information, leading to variations in how different parts of the mechanism are presented.

This identification of incompleteness does not suggest that the characterized black box or gray box simplification is a bad feature of media reports. On the contrary, it can significantly reduce cognitive load and enhance understanding (Haskel-Ittah, 2023; Keil,

2019). Moreover, many laypeople's everyday activities rely on black-boxed knowledge (Keil, 2012).

The prevalence of gray and black boxes in media reports is not surprising; these elements are inherent to how science is often communicated. They represent a significant feature of scientific communication, reflecting the complexities involved. Höttecke and Allchin (2020) previously argued that understanding the nature of science is closely tied to understanding how it is communicated. Scientific information is conveyed through various channels, influenced by interests, expertise, and sometimes intentional misinformation. Supporting students in recognizing and understanding these influences can enhance their ability to grasp the nature of science holistically, including epistemic aspects of science communication, and thus use scientific information effectively (Allchin, 2023).

Allchin (2023) highlighted the role of missing information as a lens for evaluating the trustworthiness of scientific documents, focusing on their epistemic attributes. His "Who Speaks for Science?" framework also emphasizes the importance of examining the sources of scientific claims. However, these approaches primarily address *what* information is missing rather than *why* it is absent. Our study found that missing information is an inherent aspect of scientific communication, even from well-trusted sources. Therefore, exploring the reasons behind such gaps by analyzing examples where information is either omitted or fully presented is essential.

This perspective underscores that missing information is not inherently problematic. Context and audience play a significant role in determining whether omitted details are justified. Without this understanding, students may adopt an "anything goes" mindset, equating simplified or focused omissions with misleading or deliberately incomplete information. To prevent this, students must learn to critically assess why specific information is missing. Teachers can support this by providing concrete examples that connect to topics students have studied in school. Our study offered such an example, examining how different biological mechanisms were represented in various trusted media reports.

Moreover, using gray and black boxes in communication can sometimes create the impression that descriptions of similar biological mechanisms contradict one another. This apparent contradiction arises from differences in how mechanisms are simplified or contextualized for different purposes. In the following section, we elaborate on how our findings relate to examples of school-learned biological concepts and discuss how these were presented differently in media reports. We also demonstrate how recognizing gray and black boxes can help resolve perceived contradictions.

4.2. Different Descriptions of Similar Biological Mechanisms in Media Reports

Our findings indicated that some of the characterized sub-mechanisms tend to appear in a specific mechanistic manner. For example, we found that the description of the viral entry into the cell appeared mostly as a complete sub-mechanism. A very similar and related biological process, viral exit, mostly appeared as a black box, providing no information except for the fact that the virus had changed location from inside the cell to outside of it.

In COVID-19 media information, the entrance mechanism often appeared as complete due to its relationship to the virus's name. "Corona" refers to a crown derived from the crown-shaped structure of the virus, which enables it to enter the body. In other words, an explanation of the virus's name led to a detailed explanation of the viral entry mechanism and not necessarily its purported importance in the mechanism of infection.

These entry and exit processes are not only similar, but both hold information about the selective properties of the cell membrane and how entities cannot freely enter or exit the cell. This is an important biological idea, one of the core ideas in the Next Generation

Science Standards (NGSS) (“the cell membrane forms the boundary that controls what enters and leaves the cell”; MS-LS1-2, [NGSS Lead States, 2013](#)) or the National curriculum in England, “the function of the cell membrane” ([UK Department for Education, 2014](#)). The concept of membrane transport has also been shown to be challenging due to its varying descriptions across different years of biology education ([Mouton & Archer, 2019](#)).

It is thus essential, when encountering such incomplete information in the media, to note that exiting the cell, similarly to entering the cell, is a biological mechanism and not a simple activity of one entity alone. This can be achieved by teaching students about the wording of filler terms, which often mask mechanisms such as “exit” and “enter”. Recognizing these filler terms as indicators of a black box helps avoid the confusion of thinking that the movement across the cell membrane is sometimes described as free and sometimes as selective.

Another case of closely related sub-mechanisms that are described differently can be found in the biological context of genetics. These sub-mechanisms pertain to the role of the genetic material and include the sub-mechanism of replication in the infection mechanism, the sub-mechanism of protein synthesis in the vaccination mechanism, and the sub-mechanism of mutation in the variant formation mechanism. In all of these processes, the genetic material is an entity that is involved in a different but related way. In the replication process, it is accurately replicated to create a new virus; in the protein synthesis process, it is the template for creating a viral protein; and in the mutation process, it is inaccurately replicated to create a new variant. We found that the replication sub-mechanism mostly appears as complete and focuses on the accurate replication of the genetic material. The related mutation sub-mechanism sometimes appeared as an incomplete, black or gray box. This may be confusing when encountering incomplete information about inaccurate mutated replication and complete information about accurate replication. How can mutations occur when the detailed mechanism describes an exact duplication of the genetic material? Recognizing that the mutation mechanism is described in a black box manner can, instead of causing confusion, highlight what is missing and encourage focusing on the specific differences in cases where replication involves mistakes.

Another potential source of confusion is related to the idea of protein synthesis. According to our findings, the protein synthesis sub-mechanism was mainly described as a black box. In the two above cases, the role of the genetic material was described as creating more copies of the genetic material, and this mechanism is elaborated. The genetic material appears to have a different role in the vaccination mechanism: creating a protein.

From a science education perspective, research in genetics education has shown that students have difficulties understanding the role of the genetic material (e.g., [Donovan, 2014](#); [Duncan & Reiser, 2007](#); [Gericke et al., 2013](#); [Haskel-Ittah & Yarden, 2017](#)). For example, students do not understand the role of proteins in genetics and how they may be related to the trait or the genetic material ([Gericke et al., 2013](#); [Haskel-Ittah & Yarden, 2017](#)). In the cases of the mechanisms discussed here, the roles of replicating and creating the protein envelope are both presented, while the first is mostly elaborated, and the latter may appear as a black box. Hence, it may add to the existing confusion if black boxes are not recognized as such.

This inconsistency in presentation highlights important aspects of the selective nature of scientific communication and the influence of cultural and contextual factors on what is emphasized. However, without recognizing these gaps, learners may perceive contradictions between information sources or experience confusion with previously acquired knowledge, potentially reducing their trust in the information. By explicitly teaching about the nature of scientific communication, including the role of black and gray boxes, educators can help students develop a more comprehensive understanding of biological

mechanisms and critically evaluate scientific information rather than dismissing it solely because it includes missing elements. We will further elaborate on this in the Implications for Teaching section.

4.3. Filler Terms Masking Biological Sub-Mechanisms

As previously mentioned, this study provided insights into how trusted information is often presented in a partial manner. In the preceding section, we emphasized the importance of identifying and understanding gaps in such information. However, our findings also revealed that black boxes in media reports could be either hidden or implicit. Hidden black boxes are instances where a process is skipped and is absent from the explanation, usually by using wordings such as “and then”. Implicit black boxes include a verb to imply the mechanism within the black box. These verbs have been identified as filler terms that mask a particular process in a mechanism that has not been thoroughly explained (Craver & Darden, 2013).

Different filler terms were previously categorized into more general and specific ones in terms of the causal relationship they describe (Anscombe, 1971; Cartwright, 2007). We found that both general filler terms (e.g., “cause” or “develop”) and more specific ones (e.g., “fight”, “melt”, or “mutate”) exist in a similar distribution (46% and 54%, respectively).

In this study, we also achieved a more nuanced characterization of filler terms by categorizing them into several groups based on the analogies they convey: everyday-life analogies (e.g., “fight”), analogies from different scientific domains (e.g., “melt”), and biological terms used as verbs (e.g., “mutate”). This refined classification is significant because it provides a practical guideline for identifying filler terms in biological information, making their recognition more straightforward. The simplification of complex mechanisms by using metaphors or analogies was considered a legitimate and important part of the journalist’s work for adapting information for lay readers (Brennen, 2018; Höttecke & Allchin, 2020).

Here, we claim that while this is a legitimate science communication act, its recognition as a simplification is essential. This is because these terms that are frequently used as filler terms usually hold an everyday meaning that differs substantially from their scientific definitions. For example, van Dijk and Reydon (2010) examined the term “selection”, which is intuitively understood in everyday language as an act of choosing. While this filler term bears some resemblance to the concept of natural selection, it misleadingly implies the presence of an active agent that selects. In reality, natural selection involves no such selecting entity, and selection often favors traits that are merely less disadvantageous rather than optimal. Similarly, terms like “fitness” and “adaptation” carry everyday connotations suggesting goal-directed processes, whereas the biological mechanisms are quite different. These intuitive interpretations can obscure the understanding of evolution as an undirected, population-level process driven by variation and differential survival (Reydon, 2021; van Dijk & Reydon, 2010). Given the widespread use of such filler terms in the media, failing to recognize them as placeholders, terms that gesture toward a mechanism without specifying it, can lead students to adopt anthropocentric or teleological explanations. To counter this, filler terms should be explicitly treated as conceptual gaps that invite clarification through concrete entities and processes (Brown, 1993). We will further elaborate on this in the Implications for Teaching section.

4.4. Implications for Teaching Biology

The conclusions of our study suggest that both black boxes and gray boxes should be made explicit and actively discussed in the science classroom. Such discussions can help students understand why these boxes exist, how they constrain explanations, and what

they make possible. This approach may also support students in recognizing differences between similar concepts presented with varying levels of detail, identifying the use of vague or filler terms, and avoiding intuitive, anthropocentric, or teleological explanations.

In a previous study, we showed that teachers viewed the explication of black boxes as a strategy to resolve pedagogical tensions regarding the depth and scope of content to be taught (Livni Alcasid & Haskel-Ittah, 2024). Building on that insight and considering the current study's findings on the prevalence of filler terms in media descriptions, we propose two instructional strategies to help students engage with and understand the role of black boxes in scientific discourse.

The first strategy involves directly discussing black boxes as they appear in the communication of scientific ideas, including in media reports. Our analysis found that some parts in mechanistic explanations are often represented using abstract verbs, some derived from everyday language, others borrowed from different domains, that gesture toward underlying processes without fully explaining them. These verbs suggest the existence of a mechanism, but often with meanings that differ from their everyday or scientific usage. Understanding this linguistic shorthand can reveal how science is communicated to the public and what may be lost in translation.

This oscillation between abstract and detailed representations of mechanisms aligns with the concept of semantic waves (Barreto et al., 2021; Mouton & Archer, 2019), which highlight how conceptual depth can be built through the movement between concrete and abstract explanations. Moreover, historical accounts of science show that distinctions between closely related concepts often emerged over time, suggesting that this process can be mirrored in science education (Reydon, 2021; van Dijk & Reydon, 2010). We advocate for the use of both semantic wave theory and historical conceptual development as frameworks to make students aware of how scientific understanding is constructed and communicated. The first emphasizes unpacking and repacking black boxes, while the second encourages attention to the evolving meaning of scientific terms as more mechanistic details are revealed, especially those used in media discourse, and hold an everyday meaning.

We recommend that such discussions be integrated not only when teaching mechanisms from textbooks but also when analyzing scientific media reports in the classroom. Teachers frequently incorporate media content to highlight the relevance of science to students' lives, foster motivation, or stimulate critical thinking (Nettlefold & Williams, 2021; Gardner et al., 2009; Madhuri & Broussard, 2008; Tsai et al., 2013). These instances offer valuable opportunities to reflect on how scientific concepts and black-boxed processes are presented in real-world contexts outside of formal science. Effectively leveraging these opportunities is likely to require dedicated teacher training, supporting educators in identifying black boxes and in striking an appropriate balance between highlighting essential mechanisms and accepting some level of functional abstraction.

The second strategy draws on a well-established activity involving physical black boxes, where students explore hidden mechanisms by manipulating inputs and observing outputs. Through this process, they gather evidence, formulate hypotheses, and iteratively refine their models. This activity has been shown to promote students' understanding of scientific modeling and the nature of science (e.g., Krell & Hergert, 2019; Lederman & Abd-El-Khalick, 1998). We propose adapting this activity to highlight not only the investigative nature of science but also its communicative dimension and the existence of black boxes within explanations. For instance, consider an investigation of a machine such as an automatic coffee maker. Students can begin by hypothesizing the different functions the machine performs during its operation (e.g., pouring water, adding coffee, and pouring milk). They can then create an explanation or a model that sequences these functions in the order they occur, ultimately leading to the preparation of coffee. After mapping out the

overall process, students can focus on one specific function, for example, pouring water. Using the traditional black box activity, they can investigate this function in greater depth.

While the function of “pouring” may seem intuitive, the label alone does not reveal the underlying mechanism. By unpacking what “pouring” entails through a black box approach (e.g., opening a valve, activating a pump, or tilting a container), students can appreciate that identifying a function is not the same as understanding the mechanism that enables it. This distinction highlights how scientific explanations can be further unpacked, while acknowledging that some components may remain as functional descriptions within a black box.

4.5. Limitations

Two inherent limitations of this research must be considered when interpreting the findings and implications. First, the analysis of media reports on specific mechanisms is constrained by a relatively small sample size for each mechanism (38 media reports on infection, 41 on vaccination, and 43 on variant formation). In addition, the analyzed media reports dealt with a specific biological context—COVID-19—and were only in two languages. This limited dataset may not comprehensively represent the full spectrum of media coverage of biological topics, potentially leading to incomplete insights and overlooking nuanced perspectives. However, the fact that even this rather limited sample size revealed some aspects of incompleteness suggests that incompleteness in media reports exists, and that it has various characteristics, at least some of which were identified in this study.

A second limitation originates from the definition of mechanism completeness: the definition of a “complete mechanism” employed in this study is contingent upon an agreed-upon framework. As noted, the concept of a complete mechanism is elusive because one can always go down a level and unpack more mechanistic information. Thus, this study’s definition serves as a parameter for gauging completeness within its specific context. However, this definition may not align with alternative interpretations of completeness in the broader discourse.

Supplementary Materials: The following supporting information can be downloaded at <https://www.mdpi.com/article/10.3390/educsci15070818/s1>: Table S1.

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