Examining reasoning practices and epistemic actions to explore students' understanding of genetics and evolution

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Abstract

This paper focuses on students' discursive moves and reasoning practices while engaged in a task that requires making explanatory links between sickle cell disease and malaria. Both diseases pertain to key areas of the biology curriculum, namely, genetic variability and natural selection, and are connected to the theory of evolution of living organisms. Specifically, this study examines the intersections among rhetoric, argumentation and epistemic actions in supporting students' understanding of complex biological dynamics, which are interlinked across time and space but are often addressed separately in the curriculum. Data were collected over the course of two school years (2014-2016) with a group of twenty 15-17-year-old students and their biology teacher. The findings indicate that while rhetorical moves helped students mobilize data, the use of evidence to support claims remains limited. Conversely, the type of epistemic actions enacted by the students appears to be directly related to the type of data being analysed. Hence, rhetorical moves in combination with argumentation practices appear to account for students' differential performances in building more complex explanations of evolutionary topics. We conclude that further understanding of reasoning practices and how these are shaped by discursive moves is required in biology education to help students view biological processes in a wider context and thus gain a better understanding of evolutionary phenomena.

Keywords: reasoning practices, rhetoric, argumentation, epistemic actions, evolution and genetics learning.

1 Introduction

Scientific advances in the field of genetics proceed at a rapid pace. From stem cell research to genetically modified organisms and gene therapy, genetics research is progressing with new data and new techniques (Shea & Duncan 2015) as well as new concepts and new terms (Brown 2008; Flodin 2017). Genomes are 'mapped', 'inserted' and 'designed' to suit particular functions and goals; linguistically, the 'gene' as an idiom is re-setting the ontological basis of human understanding of life towards forms of radical reductionism (Affifi 2017). Nevertheless, an important transition has occurred in the field of evolutionary biology from an idea of 'genes' as individual agents, capable of animating the organism and enacting its construction, to the recognition of the central role of the cytoplasmic body and the multi-level interactions across different levels in the living organism (Jablonka & Lamb 1995). Different and potentially competing ideas of the 'gene' would thus seem to co-exist. On the one hand, the deterministic view is supported by the idea that all characteristics of a person are 'hard-wired' by the genome (Venter et al. 2001), and on the other hand, the contextual view and the model of gene expression call for better understanding and recognition of systemic processes in genetics. Scientists agree that the relationships between genes and environment are crucial to the development of the phenotype; as Jaenisch & Bird (2003) point out, cells of an organism are genetically homogeneous but structurally and functionally heterogeneous due to the differential expression of genes. Determinism has played and continues to play an important role in shaping both genetic knowledge and its public understanding (Jiménez-Aleixandre 2014), all the way through to how students learn genetics and how they engage in epistemic practices in genetics contexts. In this scenario, the scale and extent to which systemic interactions are understood depend upon the linguistic, cultural, and political influences governing scientific research as well as the power of gene technology to suit utilitarian needs. As reported by Affifi (2017), addressing the impacts of such developments does not simply call for a discussion of 'potential risks' or threatening unknowns. Rather, the issue lies at the level of language, in "*articulating some of the semiotics effects likely to occur … and metaphors applied to modifying life"* (p. 76).

Such a state of affairs has important repercussions for education. Beyond the acquisition of concepts and the development of processes, critical literacy in science education is becoming essential for all citizens (Jiménez-Aleixandre & Puig 2012), as they are continually encountering new technologies in their everyday lives (Lewis & Wood-Robinson 2000) and are required to grapple with the different agendas that these technologies might serve (i.e., Dawson & Venville 2010). Most importantly, however, such engagement should not be seen as 'additional to' or 'external' to the acquisition of scientific concepts. Rather, it is our belief as educators that understanding biological phenomena implies first and foremost the ability to consider the factors and processes grounding our human lives, physically, socially and ecologically. Biology educators thus have important role to play in enabling students to become critical interrogators of the discourses that shape their own beliefs about humans and non-humans, as well as the beliefs that inform science policy and practice.

Grounded in the perspective outlined above, this paper draws on new theoretical perspectives both in genetics and in education, to explore the nature of students' understanding of genetics and evolution through the analysis of discourse. This paper follows the view that rhetoric and argumentation are reasoning practices that are related to each other, however their intersections have not been fully investigated (Osborne, 2001). The examination of these reasoning practices contributes significant empirical evidence to advance in the knowledge of students' learning as centred upon the construction of 'frames of thinking'. As we will see, *frames* are understood in linguistics as the mental operations underpinning the selection and use of evidence to justify a purpose or an action (e.g. referring to the gene as a 'carrier of diseases' is part of a frame of mind which defines the gene on the basis of a specific purpose, while ignoring other aspects of genetic expression).

The study will begin by reviewing the pertinent research on argumentation as an epistemic practice for building logical understanding in science. Then, we will introduce rhetorical analysis, which may be fruitful for understanding how certain linguistic strategies, such as the use of metaphors as rhetorical tools, shape and direct students' understanding of complex phenomena. Finally, the empirical section will examine the development of students' biological understanding through the lenses of both rhetoric and argumentative practices.

2 Theoretical framework

2.1 Argumentation and rhetoric in science education

Consensus exists in the science education community that reasoning practices are at the core of science and scientific knowledge construction. While early emphasis on conceptual change looked at 'talking science' as a means of uncovering students' ability to apply scientific ideas, in other words "to think with theories" (Kuhn, Amsel & Loughlin 1988), more recently, growing recognition has been given to language as a form of action, that is, 'doing science' through the medium of language (e.g., Jiménez-Aleixandre, Bugallo & Duschl 2000; Lemke 1990).

In this view, the development of argumentation as an educational practice across many areas of science education has emphasized the importance of 'discourse' as a means of introducing students to the social and epistemic practices of the scientific community. Specifically, following the work of the British philosopher Stephen Toulmin, argumentative discourse was defined as a form of structured and logical sequencing of selected evidence (data) to define qualifiers (claims) by means of supporting justifications. Toulmin espoused a practical view of argument as opposed to an absolutist one, whereby the aim of a good quality argument would be to come as close as possible to the truth, or as close to a realistic solution as one possibly can (Toulmin 1958). Thus, the key function of argument rests with the 'justifications', built upon a process of 'sifting' existing ideas against logical testing, as opposed to drawing theoretical inferences based on a set of existing principles.

Following this model, a wide range of studies have focused on students' capacities to develop scientific arguments (Osborne, Erduran & Simone 2004), that is, to make connections between evidence and conclusions. Studies have also stressed the intersection of argumentation and the application of scientific knowledge (e.g., Zohar & Nemet 2002; Sadler 2006), including the use of evidence and justifications (e.g., Sandoval & Milwood 2005; Ryu & Sandoval 2015). Nevertheless, such framing of students' discursive strategies is at odds with the recognition that the language of Western science remains a problem for many students who do not share the same epistemic communities as the scientists (Khishfe et al. 2017). While some authors have argued that the solution may lie in increasing levels of instruction and training in argumentative thinking (Weinstock, Neuman & Tabak 2004), others have pointed to the role of cultural and religious beliefs in shaping cognitive structures (Alanazi 2019) and the importance of looking further into the nature and uses of scientific language. For example, van Dijk (2016) and Brown (2008) argued for greater interrogation of metaphors such as 'cell', 'trait' or 'gene' (Colucci-Gray, Perazzone, Dodman, & Camino 2013), which convey a reified view of biological reality while leaving the original cultural roots of the terms undiscussed.

Recent studies on argumentation in science education have looked at changing instructional models based on inquiry-based learning (Walker & Sampson 2013), socio-scientific dilemmas (Shea & Duncan & Stephenson 2015) or modelling (Evagorou & Puig 2017). The inclusion of pragmatic, active and real-life learning contexts appears to support students' talking in science, and there is evidence of students' interest in controversial issues (Sadler 2011). However, this type of science learning presents many challenges in school science education in terms of how to support it and how to assess it, as well as how to research it. In particular, a key issue appears to be methodological, i.e., how to explore the construction of science learning through the use of language. On the one hand, focus may be placed on students' use of consolidated scientific notions. However, this approach will favour the analysis of scientific knowledge without capturing structures of thought, which underpin the selection of evidence and the drawing of conclusions. On the other hand, it may be of interest to explore students' abilities to make sense of multi-level questions and to use language to reason around short-term and long-term processes and scenarios. In this view, logical connections across phenomena may be neither simple nor linear, requiring students to engage with figurative speech and interpretation to account for a more complex set of meanings and possibilities (Simmoneaux & Chouchane 2011). In line with the early considerations made by Martins et al. (2001), there is a need to build a broader understanding of what argumentative performances consist of by exploring a wider array of discursive strategies, which are more common to rhetoric.

Rhetoric

In contrast to argumentation, rhetoric is not concerned with the justification of a logical move but with rule formation as part of persuasion (Billig 1987). As this author notes, different arguments may fail or succeed in persuading an audience depending on the rules upon which they have been constructed, and such rules belong to the choice of rhetorical strategies. In other words, rhetoric looks at the communicative strategies that enable particular meanings and 'images' to become normalised, accepted and disseminated via social practices (Feldman et al. 2004). From a socio-cultural perspective, rhetorical practices may be seen as 'linguistic devices' used in the organization and structuring of arguments (Billig 1987). Thinking unfolds through open and closed discussion moves, whereby logical generalizations may be combined with pragmatic considerations such as the suitability of arguments for a given audience and context. As indicated earlier, fewer studies in science education have viewed students' science learning and the work of a science teacher from a rhetorical perspective (Martins et al. 2001); hence, little is known about the role of rhetoric in argument construction and knowledge application.

Studies on language have emphasized the intersections between argumentation and rhetoric as reasoning practices (Kelly & Bazerman 2003), with Kuhn (1992) offering a distinction between *dialogical arguments and rhetorical arguments*. Both arguments are connected and they both appear in a dialogue between people with different views, requiring the same cognitive operations: propose a claim, provide evidence to support the claim and evaluate the validity of the claim. In *dialogical argument,* there is an exchange of justifications, and the argument is the product of the exchange (Kuhn & Udell 2003), in Bakhtin's (1986) sense, taking into account more than one viewpoint. However, rhetorical arguments may seem less complex in the cognitive domain, as the alternatives are not always as visible. This is particularly important for the purpose of this study, as we focus on rhetorical *arguments* because of their association with modes of communication, such as images and gesture, which shape and introduce the audience to a particular view of the world (Billig 1987). In this sense, we align with the case made by Stone (1988), arguing that reasoned analysis is political because "*it always involves choices to include some things and exclude others and to view the world in a particular way when other visions are possible*" (1988, 306).

If we apply these considerations to the study of biological topics, we suggest that argumentative moves can thus be used as cues to disclose 'small stories' that may be traced to underlying rhetorical narratives. Specifically, we are concerned with the ways in which understandings of systemic interactions are visualized and addressed by students' meaning-making strategies. We view scientific argumentation as inevitably rhetorical and scientific arguments as the coordination of claims and evidence (Sandoval & Millwood 2005). In addition, we incorporate the lenses of rhetorical analysis and specifically, as we will detail later, the moves that are used by students to warrant their claims. For example, if a gene is seen as a 'trait', it may be perceived as a personal characteristic as opposed to a nexus of multiple regulatory functions. In this case, the perception of the problem is 'framed' around an individual destiny as opposed to looking into the wider set of evolutionary phenomena. 'Frames' are thus central in the making of a story because they have the power to both mask and unmask relevant aspects of a wider narrative (Billig 1987; Pontecorvo & Girardet 1993). When operating within a given frame, the premises for actions may be taken for granted and thus left implicit unless other interpretations are encouraged and made possible. As we will see later, logical sequences, such as syllogisms in this case are replaced by enthymemes, as arguments pointing to the plausible and likely, rather than to the logically binding (Feldman et al. 2004).

To define the potential of this approach to capture students' learning, the next section will review current research in genetics and evolution instruction.

2.2 Critical connections between genetics and evolution

The teaching of biology presents several conceptual obstacles for students. For example, genetics is difficult to teach due to the many unfamiliar microscopic entities and processes involved (Freidenreich, Duncan & Shea 2011), which are difficult to visualize. Diverse instructional models have been proposed to overcome these problems, and there is an on-going debate about the adequacy of addressing Mendelian genetics before molecular genetics or vice versa. Smith, Niklas and Gericke (2015) suggest a common pedagogical technique: beginning with simplified models to scaffold more complex understandings of a subject. According to this approach, Mendelian genetics should be the starting point. In contrast, Shea, Duncan and Stephenson (2015) propose starting instruction with molecular genetics because they found that this approach improves students' learning of Mendelian genetics. Conversely, the teaching of evolution addresses processes that are often captured by different disciplines, such as palaeontology, embryology, biogeography, molecular biology and population genetics (Mayr 2002; Nehm et al. 2009). Hence, there is growing consensus about the need to enhance cross-disciplinary links across all these areas to promote students' understanding and learning (Tibell & Harms 2017).

It has also been suggested that specific emphasis on genetics during instruction may enhance conceptual change in evolution (Kampourakis & Zogza 2009), for instance, by focusing on DNA sequences while teaching natural selection (Kalinowski et al. 2010). Following Kalinowski et al. (2013), genetic knowledge is thus central for understanding evolution and overcoming misconceptions in this domain. In addition, Ferrari and Chi (1998) propose that to promote understanding of the process of natural selection, it is important for students to grasp the multiple levels of organization of living organisms as well as the different temporal and spatial scales at which evolution operates. To this end, the importance of time and space scales has been previously reported both in developing students' understanding of historical events (Pontecorvo & Girardet 1993) and in the field of ecology (Colucci-Gray, Perazzone, Dodman, & Camino 2013).

According to Alters and Nelson (2002), students' alternative ideas about evolution can be classified as follows based on their origin: a) experience misconceptions, those arising from everyday experiences; b) self-constructed misconceptions, in which students accommodate new information to their previous framework; c) taught and learned misconceptions, taught informally by other people or ~~in~~ learned in fiction; d) vernacular misconceptions, which arise from the difference between the scientific definition of a word and its everyday use; and e) religious and myth-based misconceptions. Regarding vernacular misconceptions, a clear example is metaphors, which are essential tools in science for the invention of new entities and are defined as the use of a word in a figurative sense (Brown 2008). These misconceptions may influence how students apply molecular genetic concepts and how they reason about evolutionary links (Kalinowski, Leonard and Andrews 2010). For example, a study by Jarrett, Williams, Horn, Radford & Wyss (2016) reported that participants in their study believed that sickle cell disease (SCD) is contagious and that patients with this illness die during childhood, as they believed that there is no cure or treatment. In addition, many students assume that African-American people suffer from the disease, and as carriers of the SCD trait, they do not need to know their status as they are fully protected from malaria. This case makes clear not only how the metaphor of 'gene-carrier' becomes equated to 'being the carrier of an infection' but also how the idea of immunity due to a prior or existing infection is confused with other adaptive and/or ecological effects. Finally, as we will address in this study, vernacular misconceptions may be associated with values and racial attitudes (Puig & Jiménez-Aleixandre 2011) which emerge during the process of argumentation as fallacious justifications for causes and effect. Hence the study focussed closely on the use of language to elicit awareness of sensitive issues in the biology curriculum.

2.3 Focus of the study

While the relation between ways of thinking and talking has been prevalent across many areas of science education (and not only strictly in argumentation), the intersections between rhetoric and argumentation have not been fully investigated (e.g., Martins et al. 2001; Osborne 2001). Arguably, such a gap accounts for a missing dimension in science education research, considering how cultural practices – mediated by rhetoric – interface with argumentation, and which may account for the range of arguments deemed possible or valid. This paper proposes that recovering the rhetorical dimension in the analysis of reasoning practices in science education can thus provide important cues on how students can gain understanding of complex and interconnected biological topics. Moreover, following previous studies on argumentation in genetics education (Jiménez-Aleixandre, Bugallo & Duschl 2000), other frames are explored, such as epistemic actions in students' dialogue. In this study, we specifically address the learning of evolution and genetics together.

~~To define the potential of this approach to capture students' learning, the next section will review current research in genetics and evolution instruction.~~

Research questions

This paper seeks to study the interconnections among rhetoric, argumentation and content knowledge, particularly in the fields of genetics and evolution, with the goal of uncovering the critical dimension of scientific discourse. In this view, scientific discourse is not simply considered a means to 'find the answers' but as a process to enhance critical and reflexive thinking in the use and selection of evidence.

Two research questions guided the study:

1) What frames of thinking emerge from the examination of students' rhetorical moves and use of evidence when they are learning about topics in genetics and evolution?

2) What epistemic actions help students to make explanatory links between genetics and evolution?

3. Methods

3.1. Context of the study

The task analysed in this paper is part of a longitudinal case study conducted over the course of two school years (2014-2016). The participants were twenty 15- to 17-year-old students from rural and urban areas in a state school in the centre of X (for review). The criteria for selecting the school included i. a student population that mirrors (blinded)'s overall population and ii. teachers in the Biology and Geology department who were interested in being part of the study.

The two teachers involved in the project had previous experience working with models in the classroom and both have more than ten years of teaching experience. In particular, teacher 1 (T1) was involved in a previous research project about learning geology through modelling. He was in charge of the implantation of all the activities. Teacher 2 (T2) was not familiar with modelling instruction so, his role was supporting T 1. T1 led all the activities, and along with T2, their remit was to help students progress with the task, addressing their questions and encouraging discourse between the students while avoiding giving answers. The role of the teachers was also that of grouping the twenty students into five groups of four students each. Their priority was to make groups allowing for an equal distribution of girls and boys, as well as distributing the students from the bilingual strand across all groups. The groups remained the same for all the tasks; slight changes to their composition occurred in the second year as some new students arrived and some students left the class.

The students participating in the project did not received instruction in modelling and argumentation nor have participated in modelling or argumentation activities before the implementation of the sequence.

3.2 Teaching sequence

The task analysed in this paper was embedded in a teaching sequence aimed at involving students in the scientific practices of modelling and argumentation while learning genetics and evolution. Both scientific practices make part of the NGSS (Achieve, 2013) and appear as part of the scientific competences in PISA framework (OCDE, 2017). The design of the sequence is grounded in design-based research methods (Tiberghien, Vince & Gaidioz 2009). This approach aims to develop learning environments that can be used as natural laboratories for education research, and it implies the use of designs for instruction, which are theoretically framed (Sandoval & Bell 2004). In collaboration with the teachers, the two first authors designed the tasks to be implemented in the classroom, taking into consideration previous research in the study of scientific practices and students' understanding of evolution and genetics. A previous open-end questionnaire was carried out. This task included five question formulated to capture their ideas about: a) scientific models; b) the model of gene expression; c) diseases with a genetic component. The results were taken into account to the design of the tasks. Moreover, an international expert in clinical genetics collaborated in this process with the goal of assessing the content validity and the scientific adequacy of the activities.

The seven tasks that make up the project were sequenced in increasing order of difficulty, both in terms of scientific practices and content knowledge. Molecular and Mendelian genetics are introduced for the first time in this school year, whereas evolution has been previously introduced although not in depth. The sequence was carried out after genetics and evolution instruction in their regular lessons.

The sequence starts with a practical task designed to engage students in building a material model of gene expression to explain SCD. The two-second tasks require the application of the model of gene expression to argue about a number of other diseases with a genetic component such as sudden death and cancer. The second task consists on looking and selecting information about sudden death to explain this disease applying the model. The third task focuses on argumentation and asks the students to make health-related decisions about genetic screening. The fourth and last task of the first year asks students to draw connections between genetics and evolution and explain the relationships among them in the context of making links about two human diseases, SCD and malaria. This is the task analysed in this paper. The second school year students participated in three new tasks. The first one requires them to work on the definition of models in science and its purposes. The second one asks to apply the model of gene expression to an animal disease and the last task seeks the development of a model of evolution.

3.2.1 Task: Explaining the links between SCD and malaria

Students participating in the project have not been involved previously in argumentation and modelling instruction. However, when students carried out the task analysed in this paper, they were already familiar both with modelling and argumentation tasks. Following Kalinowski et al. (2010), this activity seeks to help students construct explanatory frameworks and make explicit connections among concepts in the context of molecular genetics and evolution. In this paper, we report on the last activity of the sequence (blinded, under review).

The reasons for selecting SCD and malaria are as follows: a) among the scientific community, they are well known for having an evolutionary relation; b) they are topics that can be used to address the widespread difficulties reported in the educational research literature concerning the understanding of and relation between these illnesses (Jarrett, Williams, Horn, Radford & Wyss 2016); and c) they are relevant to the students, as SCD was recently included in the screening test in (Country, for review). Students have to apply notions previously used, such as Mendelian and molecular genetics, as well as evolution, to describe the relationships between malaria and SCD.

The task was introduced by T1 through a short discussion with the students. The driving question was presented as follows: "SCD and malaria, is there any connection between them?" To try to answer the question, students were provided with a) four numbered envelopes with information and b) a piece of cardboard to settle the pieces of information and write down their conclusions. Students were instructed to open one envelope at a time in numerical order and discuss the information provided in order to write down their conclusions. This step was repeated four times, each time with a different envelope, after having had the chance to revise all previous conclusions in the light of new evidence. Research shows that students often fail to provide data for their own claims and fail to demand data from each other (Ryu & Sandoval 2015). Hence, the task was designed to encourage students to use evidence to justify their claims by giving them different data in a structured manner.

The information was divided into four sets arranged in chronological order, including different types of information related to malaria and SCD, such as historical, diagrammatic or genetic. The reason for using a chronological order was to recreate the process that scientists follow, using the evidence available to build a hypothesis and modify it as new evidence emerges. The information was presented both in textual and visual form, as scientific meaning is derived from both modalities of representation (Lemke 1992, 1998). The information provided is thus summarized in table 1, alongside the knowledge of genetics and evolution that was required, and a brief description of the epistemic strategies needed to solve them. Students completed the task in one session of 50 minutes.

Table 1 Information provided in each envelope to prepare for the task.

[insert table 1]

3.3 Data collection and analysis

One camera and one audio recorder were placed at the table for each small group in order to transcribe students' discussions. The first and second author attended all lessons as observers; they took field notes without interfering with the development of the activities. Additionally, all small-group cardboards were collected for analysis.

The focus of the analysis is on the oral debate of group 1 because it was the only group in the classroom that actively engaged in argumentation for all the tasks of the unit; they also built a sophisticated model of gene expression in task 1, which was necessary for reasoning about SCD in this activity. The analysis focused on i. rhetorical moves (Feldman et al. 2004) and the use of evidence with the goal of revealing different frames in the students' discourse (Pontecorvo & Girardet 1993); ii. epistemic actions and the levels of acquisition of argumentative practices (Sandoval & Millwood 2005; Ryu & Sandoval 2015). Figure 1 summarizes the steps involved in the analysis process. The first three stages provided evidence for answering the first question, while the second question was addressed in the fourth stage.

Fig. *1* Stages of analysis

[insert fig 1]

<u>Stage 1:</u> The entire session was transcribed, and a total of 404 turns of speech or speaker turns (Edwards, 2001) were identified. The transcription was read in several iterations by the first author in order to examine the students' discourse.

<u>Stage 2:</u> Rhetorical moves and use of evidence were examined in students' discourse. The unit of analyses is the turn of talk, and in each turn, a rhetorical move and use of evidence can overlap. One rhetorical move can also include one or several turns of speech, as is the case for the use of evidence. For the identification of "rhetorical moves", we built upon previous categories established in the literature addressing rhetoric and discourse analysis. Particularly, genre analysis was applied, and we followed Swales' (1990) definition of "rhetorical moves" as 'linguistic strategies' or 'devices' that are employed to advance an argument or strengthen a persuasive appeal. The four categories taken into consideration included enthymemes and syllogisms as indicated previously as well as rhetorical questions and appeal to examples. We will describe them in turn. The role of the enthymeme is central. *Enthymemes* can be defined as syllogisms in which one or more parts are not explicitly mentioned or are probabilistic (Feldman et al. 2004). The missing part works as a persuasive tool to connect with the audience, which supplies their beliefs or what they are induced to believe (Feldman et al. 2004). During discourse, the construction of enthymemes shows attempts to explain a phenomenon. The evolution of the enthymemes draws together the developing scenarios students are constructing, such as the different explanation for the origin of SCD. Thus, each enthymeme was analysed to identify the unstated and stated premises.

Rhetorical questions are used in the discourse to persuade the audience, and they usually reveal an option different from the ones proposed in the discussion. They may enable participants to look for a different facet of biological phenomena or review earlier conclusions. In the context of this study, rhetorical questions pointed to attempts to either close or support the exploration of a question or a possibility that may not have occurred before.

Appeals to examples are part of inferential thinking. In our everyday lives, we use examples to explain processes or feelings when looking at similarities and making comparisons between things. In biology, examples are used to explain a phenomenon in different contexts, such as height, diverse human performances and diseases, which may result from gene expression (Puig & Jiménez-Aleixandre 2011).

As the task analysed in this study requires students to build conclusions using data, we believed it was relevant to analyse which data were used *and how* students used them to support their claims. For this purpose, we adapted a rubric provided by Ryu and Sandoval (2015). The authors looked at causal structure and coherence, citation of evidence, and use of justification in the students' written arguments and identified 4 levels for each of the four criteria. In this study, which focused on students' oral discussions, we were able to adapt the original rubric to define three levels capturing the students' use of evidence:

Level 1: One or more pieces of evidence are cited or only mentioned.

Level 2: Evidence is presented and described, but not all data are explained.

Level 3: Relevant evidence is provided to support claims, and all available data are explained.

For the coding process, we differentiated the data provided in the task (see table 1) from the information retrieved from everyday life and/or school knowledge. The identification of these categories was an iterative and interactive process that involved two researchers reading the transcriptions independently, while the third author reviewed the categories to ensure the inter-rater reliability of the study. Disagreements and problems that emerged in the coding process were resolved through continuously revising the variables and were discussed until a consensus was reached among the three authors.

<u>Stage 3:</u> following the identification of rhetorical moves and the use of evidence as described in stage 2, we then progressed to the identification of 'frames' by following the definition of Pontecorvo & Girardet (1993), whereby a frame "is part of a discussion that is characterized by a discursive activity and by a related cognitive function". The identification of the frames would thus involve the identification of the central idea elaborated by the students and how this idea was defined by the use of evidence available and the rhetorical moves being used. In line with the description of the rhetorical moves offered in stage 2, different discursive functions may serve the purpose of either closing or opening up avenues for interpretation according to the students' meaning-making processes.

<u>Stage 4:</u> Finally, to capture the range of meanings available to the students, the analysis looked at the reasoning sequences where epistemic actions were carried out. Epistemic actions relate to "the explanation procedure used for the interpretation of particular events" (Pontecorvo & Girardet 1993). Accordingly, students' fragments of discourse were coded according to epistemic actions following the rubric proposed by Pontecorvo & Girardet, which comprises five categories: *1. Terminological and conceptual definitions; 2. Categorization of social actors and of sociohistorical phenomena; 3. Locating events and phenomena in time and space; 4. Interpreting actions, plans and intentions of social actors; and 5. Locating actors and actions in their historical context*. The rubric was originally designed to analyse students' discourse about a historical event. In our study, discussion was not solely focused on historical events, whereby many human actors are visible and traceable. In this context,

a more economical choice was made to merge the second, fourth and fifth categories into one. This new category focuses on the actors that are part of the phenomenon that combines concepts from genetics and evolution. In addition, the third category was sub-divided into two so that the variables of time and space can be coded separately. In sum, four epistemic actions were identified as follows:

1) *Locating events and phenomena in time*. Turns of talk in which students deal with the time scale, trying to order or situate events in a period of time.

2) *Locating events and phenomena in space*. Turns of talk in which students try to establish the geographical space in which the events are happening.

3) *Designating terminological and conceptual definitions*. Students discuss genetic concepts and relate them to the disease being addressed, such as differentiating SCD from the SCD trait.

4) *Interpreting actions, phenomena and intentions of actors*. Students focus on the participants and protagonists of the events, which can correspond to human beings (people suffering the disease), other animals (mosquitoes causing malaria) or the illnesses themselves.

These epistemic actions were coded in the transcript and can comprise one or more turns of speech, and several actions can appear in the same turn of speech.

4 Results

4.1 Frames of thinking and reasoning practices about genetics and evolution

To address the first research question – *What frames of thinking emerge from the examination of students' rhetorical moves and use of evidence when they are learning about topics in genetics and evolution?* – we first proceeded with the examination of rhetorical moves and the accompanying use of evidence. Three frames emerged from the analysis, and examples are provided to illustrate the difficulties encountered by the students and how they addressed them.

Frame 1: Identifying the origin of SCD in the African community

This frame lasted for 111 turns of speech and corresponds to the first step of the task, during which students analysed historical data (see Table 1). Students focused on explaining the origin of SCD using the first set of data provided. Throughout the discussion, they held the hypothesis that the disease originated in Africa, arguing that the first cases were found in the Afro-American community. This conclusion appeared both in this frame and in other frames. Table 2 shows the notions students mobilized and discussed in this frame, as well as the rhetorical moves and levels of use of evidence operated in the discourse.

Table 2 First frame: analysis of reasoning practices

[insert table 2]

Examples of the discussion around each notion are displayed in the table. Students concluded that the disease originated in Africa and discussed how the disease was spread, whether by contagious effects or by inheritance. The socio-historical contexts of the origin and discovery of the disease were debated, as was the issue of slavery and how it could affect the spread of the disease. For instance, example 81 in table 2 shows how students discussed whether the diseases could have been spread in the community through genes.

As table 2 shows, students use more evidence when they are discussing the origins of SCD and the socio-historical context. Moreover, the highest level of use of evidence occurs when the students are addressing the origin of the disease (four out of nine times compared to the other notions). Regarding the data that students use as evidence, data provided in the envelopes and data retrieved from everyday knowledge were used equally. For instance, some information retrieved includes references to the fact that Afro-American people had to marry Afro American people or/and that SCD is genetic.

Regarding the rhetorical moves, the most frequent are the enthymemes and syllogisms, with a total of 20. In contrast, rhetorical questions and appeals to examples are identified two times each. In table 2, there are examples from the first two categories; for instance, in turn 103, a syllogism is identified because students are trying to build an explanation about the origin of the disease by connecting claims.

More rhetorical moves seem to appear in relation to the origin of the disease and then to the socio-historical context. These results are in line with those previously described related to the use of evidence. The excerpts featuring the highest levels of use of evidence are usually related to the appearance of enthymemes and syllogisms. At the end of frame 2, the students elaborated their conclusions by stating that the transfer of the disease occurred first, geographically, through the slave trade and movement of people, and subsequently, through marriage:

> *We think that the disease was originated in the Afro-American community where there were no medical records. A man was transferred to America as a slave with SCD. He, later, became a fugitive slave. In America, in the past, black people could only marry black people. This way, they passed to their offspring the disease originated in Africa, and a consequence, at the beginning of the XX century the causes of SCD were among the Afro-American community.*

Interestingly, the notion of the 'fugitive slave' appears to function as the missing secondary premise in the students' story and one that allowed the students to account for an agent that could 'spread' the disease. In this case, we can see an underlying narrative of the metaphor of the 'gene' as 'carrier of a defect' that is being carried by a non-compliant slave.

Frame 2: Identifying the pattern of inheritance of SCD

The second frame matches the second and third parts of the task (envelopes 2 & 3). Students focused on the differences among the phenotypes and the genotype of SCD and how they relate to each other. The information provided consisted of a family tree to complete, diagrams with molecular information about SCD and malaria (electrophoresis), and graphs relating the amount of malaria parasite found in healthy people and people affected by SCD (see Appendix 1). This frame lasted for a total of 221 turns.

Table 3 Analysis of reasoning practices supporting the identification of frame 2.

[insert table 3]

Table 3 shows the nine notions identified in students´ talk, as well as the rhetorical moves and levels of use of evidence operated in the discourse. These notions are related to Mendelian and molecular genetics as well as to information about malaria and the geographical distribution of the diseases. Most of the time, students explore the possible causes of the pattern of inheritance of SCD and use notions related to genetics, such as phenotype or genotype, to reach a conclusion: the inheritance follows a dominant-recessive gene pattern. In addition, students relate that conclusion to the information provided about malaria and check whether their conclusion matches the new information provided. For instance, example 313 in table 3 shows that students relate the information about haemoglobin mutation to their previous conclusion that the disease originated in the African community.

The highest levels of use of evidence were achieved more often when students discussed the genetics of SCD. This notion is also the one where students more frequently use evidence. Moreover, while arguing about genetics, students perform more rhetorical moves than for other concepts, not only enthymemes and syllogisms appear but also a rhetorical question, exemplified in example 122. While completing the family tree, students try to identify the pattern of inheritance of SCD and discuss the possibility of it being a sex-linked disease, as exemplified in turn 169 on table 3. The conclusions reached in this frame are as follows:

> *The inheritance [of SCD] is not sex linked and it follows the Mendelian rules. If an Anopheles mosquito bites you and you do not suffer from SCD, malaria affects you stronger. If an Anopheles mosquito bites you and you do not suffer from SCD, but you have the SCD trait, malaria affects you softer. If an Anopheles mosquito bites you and you do suffer from SCD, malaria does not affect you or affects very softly*.

Students explain how SCD is inherited and give reasons for the relationship between malaria and SCD that is observable in the graphs (see appendix 1). They make a direct link between the two diseases: when there is SCD, malaria does not affect the individual as much.

Frame 3: Making evolutionary links between SCD and malaria.

Table 4 shows the linguistic analysis that leads to the identification of frame 3: *Making evolutionary links between SCD and malaria*. The different notions that emerge from the analysis of the levels of use of evidence and rhetorical moves are exemplified. This frame corresponds to the final part of the task, when the students use geographical and biochemical information to reach a final conclusion about the relationship between SCD and malaria. The evolutionary knowledge emerges as students describe SCD as a protection against malaria, exemplified in turn 345 in table 4.

Table 4 Frame 3: Protection relationship between SCD and malaria.

[insert table 4]

The discussion of the third frame lasted 78 turns of speech, and three notions were identified, as shown in table 4. Students used more evidence in relation to the geographical aspects, thus engaging with and trying to make sense of the visual information. However, students reached the highest level of use of evidence when discussing mutation and how mutation of the red cells could be a protection against malaria. This idea accrues a wider array of rhetorical moves, such as an appeal to an example in which a student compares protection from the disease to that provided by a vaccine (turn 368, table 3). This notion is the one with more rhetorical moves involved. Students discuss the idea that when one of the diseases appears, the other cannot. Anxo disagrees with this and believes that in this case, a disease can positively affect a person's development, showing that mutations can be positive. Their colleagues are against this idea, but in the end, all agree and write down their conclusion:

> *In Africa lives the Anopheles mosquito, and if it bites, people get malaria. This way, black people mutated the haemoglobin to have SCD. This way, suffering the disease, black people would be protected against the disease [malaria] and they would suffer it less. This way we explain how the disease was originated in Africa*.

As we can see in the final conclusion, students agree that there is an evolutionary link between the two diseases, whereas this explanation is teleological, a cause-affect explanation. They do not use the terms of adaptation or evolution, but the two notions remain implicit. In the story produced by the students, protection from the disease accounts for an idea of evolution as 'progressive improvement' as opposed to being a contingent and contextual set of regulatory adaptations. Indeed, the advantages for the mosquitoes are never discussed. The focus remains on humans as the central premise of the evolution story.

In summary, the most frequent rhetorical move in each frame is the enthymeme. Regarding the levels of use of evidence, there is not such consistency; in the first two frames, the most frequent level is the lowest, while the second level is found in the third frame. Considering the data used as evidence, there is a progressive increase from frame 1 to frame 3 and a decrease in the use of retrieved information from the factsheets.

4.2 Epistemic actions while reasoning on genetics and evolution

This section discusses the results of the second research question: *What epistemic actions help students to make explanatory links between genetics and evolution?* To answer this question, the analysis followed the categorization of epistemic actions elaborated by Pontecorvo and Girardet (1993), as described in the methodology. The analysis allowed us to identify four epistemic actions in the three frames previously described.

1) *Locating events and phenomena in time*. Students try to situate or order events along a timeline. The events are usually related to the ones provided as data in the first part of the task, such as the different cases of SCD reported in the beginning of the XX century in America.

2) *Locating events and phenomena in space.* Students try to situate, usually geographically, a phenomena or event. The phenomena or events are related to the reported cases of SCD, where SCD originated, or where people suffer from both malaria and SCD.

3) *Definition of terms and concepts*. This epistemic action relates to the turns of talk where students try to define or explain a concept. Usually, these turns are related to

genetic topics, such as the phenotype of SCD or different patterns of inheritance of the disease.

4) *Interpreting the actions, plans and intentions of actors.* Students discuss the protagonists of the phenomena and events. The protagonists can be a person or a group of people, an animal (such as the malaria mosquito) or the diseases themselves (malaria and SCD).

Tables 5, 6 and 7 show the epistemic actions that students perform in each frame, with illustrative examples. It needs to be highlighted that the same turn of speech can include one or several epistemic actions because they can be performed at the same time. The frequency of each epistemic action, its relation to the notions discussed in each frame, and their interactions are presented in the following tables.

Table 5 Epistemic actions in Frame 1: Identifying the origin of SCD in the African community.

[insert table 5]

In frame 1: *Identifying the origin of the SCD in the African community,* as displayed in table 5, the most frequent epistemic action is *Interpreting actions, plans and intentions of actors*. This epistemic action is also related to a larger variety of notions. It seems that in this frame, this epistemic action is crucial to reach the conclusion.

Conversely, the epistemic action of *Locating events and phenomena in time* does not appear very frequently, although it is important in this frame as it places the events in a particular historical context. These actions led the students to use everyday knowledge about the period of time that was relevant for them and helped them to build the conclusion. This is exemplified in table 5, turn of speech 103.

Table 6 Epistemic actions in Frame 2: Identifying the pattern of inheritance of SCD.

[insert table 6]

In frame 2: Identifying the pattern of inheritance of SCD, as shown in table 6, the epistemic action of *Interpreting actions, plans and intentions of actors* is the most frequent, appearing on its own or related to other epistemic actions. This epistemic action is the only one in this frame that is related to all notions, while the other epistemic action that appears on its own, *defining terms and concepts,* is only related to genetics. An example is shown in table 6, in turns 164-169, when Anxo and Ana discuss which pattern of inheritance is more likely to apply to SCD.

The scarcest number of epistemic actions is linked to *Locating events and phenomena in time* and *locating events and phenomena in space*, which is consistent with the data provided in this part of the task. All the notions that emerge are mainly related to genetics or molecular genetics. In turn 313, the epistemic action *Locating events and phenomena in time* appears for the first and last time, when Ana makes a direct link between the conclusions they had reached in the previous part and the new information provided, reaffirming their claims. Students make a link between the origin of the SCD in the African community and its molecular origin (the haemoglobin mutation).

In the third frame, as shown in table 7, two out of the four epistemic actions appear. More notions appeared when the two epistemic actions coincided. Students deal with genetic information and the geographical distribution of the two diseases, as well as the evolutionary link between them, which is consistent with the information provided in this part of the task.

Table 7 Epistemic actions related to Frame 3: Making evolutionary links between SCD and malaria

[insert table 7]

The idea of haemoglobin mutation being a 'protection' against malaria is repeated continuously throughout the task, and one student, Anxo, tries to convince the other students that this is the true connection between the diseases. An example is presented in table 7, turn 389.

As we can see in tables 5 to 7, epistemic actions seem to occur in the same turn of speech. We can see that in frames 1 and 2, there are at least three epistemic actions and several combinations of them, whereas in the third frame, only two epistemic actions appear (actors and space). These two epistemic actions are the ones directly related to the information provided in the task.

Therefore, the four epistemic actions identified are not equally represented, and they may or may not feature in the students' discourses depending on the information provided by the task and the students' ability to mobilize further information. While revising the transcription, it was observed that these changes in epistemic actions (this being a change a substitution, an addition or a loss) could be related to the appearance of rhetorical moves and the use of data in the discourse. For example, in frame 1, we observe twice that no discursive move is involved in a change of epistemic actions; in frame 2, such a move occurs five times, and in frame 3, no change occurs. It seems that rhetorical moves and the use of evidence help students to make changes among epistemic actions. Concerning the rhetorical moves, the most frequent in every frame is the enthymeme. Regarding the use of data as evidence, there is a pattern, as we move from the first frame to the next frame, with an increase in the level of use of evidence. This means that in the third frame, the highest level of use of evidence is the one most frequently involved in the changes in the use of epistemic actions.

5 Conclusions

Genetics and evolution are biological fields that are very much connected; nevertheless, there is still scarce evidence on how to teach them jointly while engaging students in reasoning practices such as argumentation. Recent research in science education has pointed to the need to integrate genetic concepts involved in the process of evolution as a way to help students to grasp the theory of evolution (Mayr 2002). A study carried out in the UK by Mead, Hejmadi & Hurst (2017) revealed the benefits of teaching genetics before evolution because it improves students' understanding. In our country (blinded for review), genetics and evolution are usually taught as separate topics. The curriculum presents genetics prior to evolution. The suggestion is to begin instruction with molecular genetics, moving to Mendelian genetics and then finishing with evolution. Because they are addressed in different units, teachers do not necessarily explicitly connect the different levels and topics, potentially leading to instruction with fewer links between concepts that are presented in no particular order and sometimes with a large time span in between.

This study engaged students in genetics learning prior to evolution as a way to build understanding of fundamental concepts of genetics and then apply those concepts to learning about evolution. The task required students to integrate data from different disciplines and to move across different levels of biological organization, and through time and space scales, to explain the evolutionary links between two human diseases, SCD and malaria.

The examination of argumentation and rhetoric allowed us to identify three central frames emerging from the students' discourse. Frame 1, *Identifying the origins of sickle cell disease in the African community,* shows students' understanding of SCD as a disease that originated in Africa; evidence from this frame showed how students accommodated new data to their own views. References to the fact that Afro-American people could only marry Afro-American people and to SCD as a contagious disease that was spread in Africa by an Afro-American slave, and then passed on through inheritance within the Afro-American community, appeared in students' discourse. Rhetorically in this frame, Afro-Americans appear to be clearly identified by the students as 'actors', a group of people marked by cultural *and* biological differences from other groups. We note here the implicit opposition created by the frame with other groups, such as the white American communities who were not affected by the disease. We consider this manner of framing the question to be a remarkable issue that points to the influence of cultural beliefs when students make sense of data and to the need to pay attention to this issue in biology instruction. SCD is linked to "African people" or "blacks", as other studies have previously found (Biggs et al. 2002), even though many Afro-Americans did not live in Africa. This is an example of the influence of social representations, an influence that has been previously reported in studies about the model of gene expression and biological determinism (Puig & Jiménez-Aleixandre 2011).

In Frame 2, *identifying the pattern of inheritance of SCD,* students conclude that inheritance follows a dominant-recessive pattern. They make a direct link between SCD and malaria. As in Jarret's et al. (2016) study, the students identify the mutation of haemoglobin as the cause of SCD and identify the source of the disease amongst Africans, which leads them to justify why "black people suffer SCD". In addition, students declared that carriers of the SCD trait 'do not need to know their statuses' and are protected from malaria (Jarrets et al. 2016). Following Mendelian genetics, students stated that 'carriers' of the defective gene will suffer malaria less than the non-carriers. Interestingly, what students identified as the necessity (or not) to disclose one's status is reminiscent of stigma associated with blood conditions, such as haemophilia or HIV, although in this case, the initial negative slant seems to be compensated by the possible positive effect against malaria. We can see here a rather pragmatic and linear view of genetic mutations as being directly linked to neo-Darwinian ideas of evolution as selection and survival of the fittest in a competitive environment.

In Frame 3, *Making evolutionary links between SCD and malaria,* students agree that there is an evolutionary link between the two diseases. They do not use the terms adaptation or evolution, but these notions are implicit. One student considers the mutation of haemoglobin as positive because it offers protection against malaria. In addition, the fact that the mosquito lives in Africa explains why blacks are protected against malaria, thus confirming the origin of the SCD in Africa. Again, we note the logical linearity of students' arguments as a noteworthy issue because the maps provided of the distribution of malaria also showed the prevalence of malaria in other areas outside of Africa (Europe and Asia), but students only pointed to Africa. We can conclude that the students propose naive ideas about evolution, such as teleological explanations that are supported by mechanical ideas of 'genes as agents', which manoeuvre and direct the destinies of particular groups of people. This example also supports Affifi's (2017) argument about 'habituation', that is, a way of thinking, which is established through rhetorical and discursive practices. As Affifi (2017) remarked, "*when genes are described as information-bearing entities without a sensitive and ongoing responsiveness to environmental cues, the 'logic' of the gene and the 'logic' of the environment are artificially kept at a distance from each other*" (p. 85). Preserving such a division has consequences in the way that it privileges the supremacy of certain species or groups over others. Furthermore, as emphasized by Kirschner and Gerhart (2005), we also note the impossibility of the linear logic to accommodate notions of genotypic novelty, which ends up being limited to "error" or "mutation". Not having a satisfactory or alternative explanation for genotypic novelty further reinforces ontological and methodological reductionism, buying into the idea of DNA sequencing to predict health or disease in particular groups. However, we must note that this idea can only stand by considering the environment as fixed and stable.

The analysis of rhetorical moves indicated that students mobilized several sources of information, although the discursive moves did not necessarily support high levels of use of evidence. The highest levels were mostly related to the formation of enthymemes, although students did not seem to achieve a more sophisticated idea about the processes being studied. In accordance with Tibell & Harms (2017), students struggled to build interconnected biological explanations; in particular, they had difficulties connecting biological entities and processes belonging to different levels of biological organization, between molecular genetics and Mendelian genetics as well as genetics and evolution.

For example, when looking at the analysis of the epistemic actions, *Interpreting actions, phenomena and intentions of actors* appear most frequently in students' discourse. This result is unsurprising given that biological processes involve different actors that need to be considered in relation to each other. However, this could show that further instruction before the implementation of the task is needed around the main concepts of genetics and evolution to improve students' performance, in particular related to this epistemic action. Conversely, *Locating events and phenomena in time* appear very frequently in the first frame, as this approach coincides with the reading of historical data provided to the students, but it is absent in the second and third frames. *Terminological and conceptual definitions* only appear in the second frame. This approach coincides with the students struggling to establish meaningful connections among phenotype, genotype and associated technical terms, such as homozygotes, as well as metaphors (Table 6, turn 39: recessive/dominant; and turn 32: carrier).

Such differences may be crucial for understanding why students were not able to build a complex evolutionary explanation at the end of the task. Students focused largely on human actors, and they located events within a short time frame, thus overlooking the longer-term mechanisms that may be involved in the relationship between biological, ecological and evolutionary aspects. On the one hand, they tried to fit new data into their ideas, with only one student trying to oppose to gain deeper understanding. On the other hand, despite the task being structured to continuously analyse and revise the data provided, students only used the data provided at each individual step. Consequently, they only enacted the epistemic actions that were directly related to the data being analysed. We believe scaffolding from the teacher is needed when participating in a task that requires revising the data, to improve the performance of students.

6. Educational implications and limitations of the study

Taking evidence from our findings into consideration, we believe that awareness of rhetorical discourses should be developed further by teachers to help students understand how they view biological processes in wider scenarios. This may mean helping teachers recognize the importance of 'framing' in students' discourse, the ways in which frames are connected to particular terms (Flodin 2017) and how such terms are connected to cultural beliefs. Referring back to Affifi (2017) and van Dijk (2016), metaphorical terms that are largely used in biology and to which we have become habituated will need to be examined and decontextualized to disclose their figurative meanings. Thus, tasks should not only include diverse data but also require teachers to enhance 'linguistic creativity' to enable students to view processes from different perspectives, ask open questions, and widen the range of possible links between relevant actors. This would require teachers' instruction on this matter and professional development would be helpful to achieve this goal. Moreover, social representations related to cultural and biological differences among human groups and determinist positions corresponding to the high status of genes in the social imaginary should be address in biology instruction (Puig Jiménez-Aleixandre 2011).

The difficulties to develop a scientific explanation about the evolutionary links between both diseases may have been reduced if students were provided with more time to discuss the data provided and to get used to the task procedure. Despite having participated in three modelling and argumentation tasks previous to the one analysed, participants were not familiar with a scientific-based approach. We agree with Duncan, Rogat & Yarden (2009) that participating in scientific practices should be done regularly in the classroom. Engaging in scientific-based activities effectively requires time and sustained practice, as long as teachers' training on its instruction, being this one of the limitations of the study.

Although it needs to be considered that the results of this study are not generalizable, since it is a case study research, our findings point to the need to engage students in learning genetics and evolution together and developing teaching units to address these difficulties (Kampourakis & Zogza 2008). The overall educational goal, however, is to develop a better understanding of the nature of human thought, which constitutes and is constituted by the material and ecological world we inhabit. This study has sought to trace how ideas of the 'gene' affect students' mental ecologies, and it calls for a deeper grasp of the nature of this concept in light of advances in the field but also for greater consideration of the emerging paradigm that understands information as constituted by complex biophysical interactions among genes, organisms and environments (Fox Keller 2001).

We believe the endeavour described above is an important responsibility for biology educators who are preparing students to be active participants in the social, cultural and ecological practices of science.

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