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Design principles for integrating science practices with conceptual understanding: an example from a digital learning environment on microbial resistance to antibiotics

Constantinos P. Constantinou [1✉] & Eliza Rybska [2]

We aim to illustrate the use of generic design principles to attain the integrated promotion of conceptual understanding and science competences in online enquiry-oriented learning environments. Engaging students in the development of competences related to science practices in unison with nurturing rigorous understanding of the mechanisms underpinning phenomena is thought to be valuable both for making science education more relevant to students' interests and for attaining meaningful learning outcomes. We describe the design and development of a learning environment on the socio-scientific issue of microbial resistance to antibiotics. Our effort is situated in reflective enquiry, a framework for teaching and learning in science. The learning environment seeks to promote argumentation skills and conceptual understanding of evolutionary adaptation, in unison. On the basis of theoretical grounds, we have chosen to work with five design principles, integration of epistemic practices, making evidence-based inferences, competence-oriented design, authentic and relevant context and scaffolding. The first part of the study presents the design principles that have been embedded in the learning environment and the second part provides a description of the learning environment linking the various features to the corresponding design principles. Finally, we discuss the implications of this study for research and teaching practice.

[1] Learning in Science Group, Department of Educational Sciences, University of Cyprus, Nicosia, Cyprus. [2] Laboratory of Nature Education and Conservation, Adam Mickiewicz University, Poznań, Poland. ✉email: c.p.constantinou@ucy.ac.cy

Introduction

The design and development of learning environments with the potential to improve the quality of science learning is an important mechanism for science education reform. In this context, the need to promote the development of competences relating to scientific practice in unison with conceptual understanding has been identified as an important priority (Hazelkorn et al., 2015; National Research Council, 2012). Researchers have formulated design frameworks and principles based on findings from education, psychology, and learning science. Recently, emphasis has been placed on technology-enhanced or online learning environments due to the inherent advantages of interactivity, monitoring, and feedback (Shi et al., 2021; De Jong, 2019). The attention of researchers has also turned to research on technology-enhanced or online learning environments that are designed in the framework of an enquiry-oriented learning strategy (Constantinou et al., 2018; Cai et al., 2021), often in the context of socio-scientific issues (SSI) to enhance relevance to students' interests and aspirations (Hansson et al.,2011; Hernández-Ramos et al., 2021). SSIs often relate to value-laden, controversial, socially relevant, real-world problems that are informed by science (Sadler et al., 2007) and are constrained by missing knowledge (Chiappetta et al., 1998). Engaging students to work with socio-scientific issues can be motivating and challenging because 'they embed evidence of cognitive and moral dissonance, where scientific evidence, real-time data collection, analysis, interpretation, and investigation become entangled with socio-political decisions, and where a public understanding of science is tantamount to life and death decisions at global, national, regional, and personal levels' (Zeidler and Sadler, 2023).

In this paper, we present the principles employed in designing an online enquiry-oriented learning environment on the topical issue of microbial resistance as an example of a socio-scientific issue. Microbial resistance to antibiotics or anti-microbial resistance has emerged as a challenge of global concern with implications for public health, the safety of medical procedures and institutions, as well as home hygiene routines (Ferri et al., 2017; Bloomfield and Ackerley, 2023).

The value of this paper relates to how pedagogical principles can be applied in design for learning but also in how they can be used to promote the combined promotion of competencies and conceptual understanding. This approach holds enormous potential in promoting a paradigm shift in science education with substantial improvements in the quality of learning outcomes (Papadouris and Constantinou, 2017).

Theoretical background

Social constructivism posits that learner construction of knowledge is attained through social interaction, interpretation, and understanding. Learning emerges through active knowledge construction, which is evaluated through the development of consensus between individuals (Adams, 2006).

Consistent with this, enquiry-based teaching and learning is a complex process of sense-making and constructing coherent conceptual models where students approach the study of phenomena by formulating questions, gathering evidence, and investigating to find answers. Through this framework, students collaboratively build new understandings, meanings, and knowledge, communicate their learning to others, and apply their learning productively in unfamiliar situations. Enquiry-based science education engages students in: i) authentic, problem-based learning activities, where there may not be one correct answer; ii) experimental procedures, experiments, and 'hands-on' activities, including searching for information; iii) self-regulated learning facilitated by teaching sequences where the emergence of student autonomy is emphasised; and iv) discursive argumentation, negotiation of ideas and communication with peers ('talking science') (Hazelkorn et al., 2015; Constantinou et al., 2018).

Within this paradigm, nurturing the development of competences and coherent conceptual understanding in unison has received special attention. It is a challenging educational goal that is nevertheless thought to be worthwhile in promoting rigorous learning, critical thinking, and creativity (Papadouris et al., 2018). Educational standards have come to emphasise competences, such as argumentation, scientific modelling, problem-solving and technological design, as robust educational goals that serve to enculturate a new generation into the values and practices of science and technology (NRC, 2012).

To make it possible for educational efforts to respond to the challenges of meeting these goals for rigorous learning, tools in the form of structured learning environments, guidelines for teaching and formative assessment instruments to provide feedback for learning progression are of paramount importance. The formulation of design principles for the development of such educational artefacts can be a useful strategy both for consistency and replication (Quinton, 2010).

Design principles for an enquiry-oriented learning environment

In this section, we present the pedagogical tenets that have guided and informed the design of an enquiry-oriented learning environment on 'Microbial Resistance.' The tenets utilised in the design were derived from social constructivism and the framework of enquiry-based teaching and learning for the purpose of designing a learning environment that facilitates the attainment of targeted learning outcomes on a topic of socio-scientific interest. Figure 1 presents the theoretical framework and the principles that emerged for the design of the learning environment.

Effective learning through the integration of epistemic practices. In recent decades, there is increasing emphasis on educational reform that promotes shifts away from the notions of learning as the transmission of knowledge and science as the accumulation of uncontroversial facts. Instead, the science education research community strives to promote and facilitate the study and understanding of science as a human enterprise (Driver et al., 2000; NRC, 2000). Within this effort, enquiry–based learning has gained substantial support as a learning approach that focuses not only on understanding of content but also on cognitive processes that students engage in during the exploration of a scientific topic thus also promoting the development of scientific practices (Constantinou et al., 2018). Scientific practices have been proposed as an integrative set of competences, which emerge as young people engage with active sense-making, investigation, problem-solving and project work with scientific issues of contemporary relevance (Kuhn et al., 2017).

Singer et al. (2000) included enquiry as one of the design frameworks that guided their development of several sets of curriculum materials enhanced with the use of appropriate learning technologies. In our endeavour, we regarded enquiry as the core teaching-learning framework and developed around it by employing design principles that originated from educational psychology and education studies addressing the issue of how people learn by constructing meaning, retaining knowledge and actively using it in co-creation in response to a driving question or a problem-based challenge. Following recent emphasis on the development of learning environments that engage students in

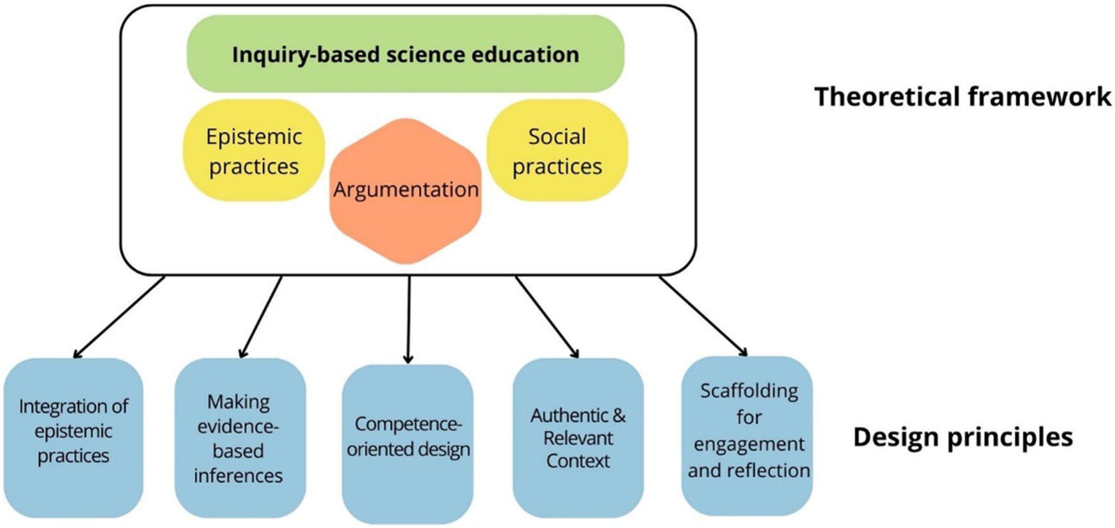

Fig. 1 Formulation of theoretically grounded principles for the design of the learning environment.

authentic enquiry tenets, we expanded our focus to incorporate two other elements of scientific enquiry that are often neglected: epistemic and social practices (Grandy and Duschl, 2007; Chinn and Malhotra, 2002). Thus, the designed learning environment on *Microbial Resistance to Antibiotics* entails key aspects of enquiry, such as examining and analysing data, interpreting data, and drawing conclusions, all of which have been integrated under the prominent scientific practice of argumentation (Sandoval and Reiser, 2004; Jiménez-Aleixandre and Crujeiras, 2017; Sandoval and Millwood, 2007; Kolstø and Ratcliffe, 2007). A significant part of scientists' time is devoted to reading other scientists' communications, building on each other's work and exchanging well thought and grounded arguments, to support their theories or to evaluate other scientists' claims (Chinn and Malhotra, 2002). The practice of argumentation is a fundamental tenet of scientific enquiry and should also be considered a significant goal in teaching and learning science. Nurturing argumentation competence as an integral part of science instruction is one way of promoting students' epistemological development (Kuhn, 1991; Duschl and Osborne, 2002; Iordanou and Constantinou, 2015). Argumentation also provides a bridge to enhance the relevance of science learning for resolving issues that concern students' daily lives. At times of open access to scientific and other information and the widespread use of AI tools, students need to be able to identify and critically evaluate information of relevance to make informed decisions on any issue that concerns them and they also need to have the capacity to communicate those decisions in a clear, understandable and persuasive manner according to the audience (Zeidler, 2014; Valladares, 2021).

Sandoval and Reiser (2004) coined a term for an equivalent overarching principle used in the development of their learning environments and scaffolding tools. They referred to their key principle as 'grounding process in the products' and, for their learning environments, the focus (product) was scientific explanations. According to Reiser et al., (2001), while students are grappling with data to construct explanations, they employ various cognitive and social skills that are important for science learning. This principle is also in line with Jonassen's (1999, p. 222–223) 'model' for designing learning environments. At the heart of his model is the case or problem driving the learning, which is subdivided into three important components, context, representation, and manipulative space. The manipulative space of the 'problem' is the mindful engagement of the student in manipulating an epistemic artefact, e.g., a simulation (or physical objects) or developing a coherent argument.

Our own efforts sought to establish a view of science as a human construct and this was facilitated by promoting conceptual understanding and the competence of argumentation in unison. In Sandoval and Reiser's (2004) terms, the 'product' of our study, was the written arguments constructed by the students themselves in an effort to support their claims with valid and sufficient evidence identified from resources provided within the learning environment. As shown in Fig. 1, IBSE and scientific practices create a space for making connections to the nature of science as part of teaching and learning science. We have emphasised making evidence-based inferences as a crucial element that allows students to develop a sustained interest in science and their competence in making informed decisions.

Making evidence-based inferences. The overt emphasis on '*making evidence-based inferences*' originates from the design principle formulated by Sandoval and Reiser (2004), which they termed as 'link evidence to causal claims'. This also relates to the difficulty that students often encounter in grappling with data and in backing their hypotheses/claims with appropriate evidence. Kuhn (1991) found that students and adults had particular difficulty in coordinating evidence to claims. Most of the participants in her studies supplied pseudo-evidence, which reiterates the theory and thus cannot be accepted as 'genuine' evidence. Kuhn's (2010) interpretation of the use of pseudo-evidence is that students fail to conceptualise the different epistemological statuses between data and explanation. Sandoval and Reiser (2004, p. 351) also agree with this position stating that students 'view explanations as being embodied in data' and consider this view as being impregnated by instruction of science in schools that is based on the 'over-objectification of data'. Thus, it is imperative for designed curricula and learning environments to include explicit activities and scaffolding that help students overcome those difficulties. Digital learning environments offer an additional advantage when it comes to data due to the multiple data representations that can be supported by technology, aiding students in employing their creativity in interpreting the available evidence (Krajcik et al., 2000).

In addition to spotlighting the different epistemological status of data and explanations, which is vital in the construction of causal explanations and cogent arguments, it is also important to include activities that engage students in evaluating data. Using credibility criteria, students can formulate judgements about data sources and about the completeness and validity of the evidence itself (Nicolaidou et al., 2011). These types of activities offer guidance to students throughout their investigation in recognising relevant and reliable data.

The creation of learning environments that help students to develop their abilities to reason from evidence and participate in scientific argumentation is recognised as a priority in science education (AAAS, 1993; NRC, 1996, 2001, 2007). According to Duschl and Gitomer (1997), this involves prioritising competences such as 'the development of thinking, reasoning, and problem-solving skills to prepare students to participate in the generation and evaluation of scientific knowledge claims, explanations, models, and experimental designs' (p. 38).

Competence-oriented design. Since the beginning of the XXI century, a concerted effort by many educational researchers has been made to promote argumentation in the science classroom (Driver et al., 2000; Duschl and Osborne, 2002; Kuhn and Udell, 2003). This effort has been promoted from four distinct educational perspectives at the same time: understanding the nature of science (Driver et al., 2000; Sandoval and Reiser, 2004), engagement in scientific public debates on critical issues for promoting citizenship (Erduran et al., 2004), development of cognitive skills (Jiménez-Aleixandre and Erduran, 2007) and scientific literacy (Cavagnetto, 2010). Argumentation can refer either to written arguments, rhetorical argumentation when someone formulates a line of reasoning to support a claim (argument as a product), or social, dialogical argumentation when two or more people engage in a debate (argument as a process) (Wegerif, 2019). These two types of argumentation operate on a similar set of skills (Kuhn, 2005; p.113; Driver et al., 2000). The practice of argumentation strengthens efforts to develop scientific literacy through active participation in evidence-based communication and also highlights the connections between enquiry-based science and developing an understanding of the nature of science.

Students encounter numerous difficulties while formulating arguments or participating in argumentative discourse. Students' difficulties include coordinating evidence with claims (Kuhn, 1991), focusing on superficial evidence (Zeidler et al., 2009), supplying insufficient evidence (Sandoval and Millwood, 2005), providing reasoning that does not adequately connect the evidence with the claim (Bell, 2000), and handling cognitive overload in argumentative discourse (Kuhn, 2010). These research studies demonstrate the complexity of argumentation competence and suggest explicit teaching and extended engagement of students in aspects of argumentation (Kuhn and Udell, 2003; Larson et al., 2009).

In an effort to support students in garnering their resources to overcome these difficulties, our learning objectives aimed for students to: 1) formulate arguments that integrate elements of Toulmin's (1958) model (claim, data, warrant, backing, rebuttal), 2) recognise the different roles of data and warrants, 3) evaluate evidence and elaborate their reasoning with an explicit intent to connect the data with their claims, 4) evaluate arguments constructed by their peers, and 5) refine their arguments based on the received comments.

The adoption of epistemic and social practices as educational goals encouraged us to seek an authentic context for students' scientific inquiries that would be conducive to placing emphasis on the development of coherent and conceptual models but would also be topical and appreciated as relevant to students' interests.

Authentic and relevant context: a socioscientific approach. The context of a set of curriculum materials or learning environment is critical for its success. Various researchers have devoted time, effort and space in their work to exemplify the multifaceted role of context. Linn et al., (2004) treat context under the design principle of 'making science accessible'. Singer et al., (2000) include 'context' in their design principles and state that curriculum context needs to be meaningful and challenging for the learner. Meyers and Nulty (2009, p.567) claim that students' learning improves when teaching and learning materials are authentic, real-world and relevant to students' lives.

The issue, problem, or question guiding the whole learning process should be authentic and adequately ill-structured, thus allowing students to make the associations and connections required for knowledge transfer into unfamiliar and complex real-world problems. Authenticity has a diverse meaning. The somewhat oversimplified and circumscribed meaning sometimes ascribed to authentic is a personally relevant or interesting topic. The more widely accepted definition refers to activities that engage students 'on the same type of cognitive challenges as those in the real world' (Jonassen, 1999, p. 221). The essence is that science thinking and co-creation should be situated in real, important, and complex issues that are at the centre of attention and are meaningful to students. Nonetheless, the transfer of real-world, scientifically-based problems into the classroom requires adaptation to make them suitable for the students. Adaptation is the modification of the entire content (e.g. enclosed information, data representation, and methods) to match the cognitive level and prior knowledge of the students (Crawford, 2012) and to support constructive pathways for sense-making and co-creation. Building on students' existing knowledge, ideas and experiences is not a new construct; it has been around for a long time, but it continues to receive significant attention as an important priority in design guidelines (Driver, 1989; Krajcik et al., 2000).

Contextualising a learning material or environment with a problem that is personally relevant to students encourages engagement and motivation (Jonassen, 1999; Herrington et al., 2004). Edelson, Gordin and Pea (1999) recognise student motivation (content-focused motivation) as the first that learning materials' designers should address by creating legitimate interest. Students' interaction with a learning environment or curriculum could be further enhanced by framing it with a pedagogical scenario. For example, in Kyza et al., (2011) a scenario was used to increase the appeal of the investigation. So, after students completed their investigation and had constructed their product (explanation), they had to communicate their findings on the issue of *what caused the sudden death of a large number of flamingos in a Salt Lake*, by writing a final report for use by the Fisheries Department. Similarly, in mission-driven learning environments, students, acting as scientists, are scaffolded to address a socio-scientific issue using evidence and tools for processing that evidence (De Jong et al., 2012). Using a pedagogical scenario strengthens the connections that students make with socio-scientific issues and creates a sense of ownership for their learning as a mission.

Scaffolding for engagement and reflection. *Scaffolding*, at its core, is any process that guides and assists a learner to activate their cognitive and epistemological resources and to exert the perseverance needed to overcome difficulties that make the completion of a task unattainable (Quintana et al., 2004). Providing appropriate scaffolding is integral to the design of learning materials and relies on design principles such as making thinking visible and offering tools for co-ordinating theory with evidence. Education reform can be advanced significantly by the development of learning materials that are challenging and engaging and also require students to employ substantive content knowledge, higher-order skills and processes. In this effort, it becomes imperative to anticipate student difficulties and plan for interactive resources in advance, on how to resolve them.

Scaffolding is separated into two types depending on 'who' is the source of the assistance provided to the students: teacher (or peer)-enhanced scaffolding and technology-enhanced scaffolding. It is also possible to blend combinations of the two in a learning intervention. Teacher (or peer)-enhanced scaffolding taking place face-to-face or online is concerned with the different approaches of human collaboration that may support students in accomplishing the task at hand. Technology-enhanced scaffolding can take various forms depending on the design purpose. Examples of scaffolding (software) tools include maps, graphic representations, reminders, prompts, templates and reflection tools. Despite the differences between the two types of scaffolding, they share the same underlying principle, which involves nudging students to activate their resources and bringing them to bear on the task at hand as well as helping students overcome learning impasses and reach goals that they never thought possible (Quintana et al., 2004; Lund, 2004). Raes et al. (2012) investigated the effect of different types of scaffolding in a web-based learning project and their findings support combined scaffolding as the approach that facilitates both knowledge acquisition and development of metacognitive skills. However, the challenge when designing scaffolding is to find the balance between under- and over-scaffolding; it is important for students to have opportunities to learn through failure, to have the required support in order not to feel incompetent, and also to work with gradually faded scaffolding in a way that enhances emergent autonomy (Guzdial, 1994).

In our study, we employed the framework for designing scaffolding that was proposed by Quintana et al., 2004, p. 341). The framework revolves around three processes: sense-making (basic operations for testing hypothesis and interpreting data), process management (strategic decisions involved in controlling the enquiry process), and articulation and reflection (process of constructing, evaluating and articulating what has been learned). Specifically, emphasis was given to creating opportunities for students to externalise their thinking and reflect on what they have been working on, reducing the complexity of tasks or concepts and social scaffolds to support constructive peer-collaboration. Collaborative learning implicates students in cognitive activities, such as explanation and argumentation, in their attempt to co-construct knowledge, develop consensus, and co-create (Dillenbourg, 1999).

Design methodology

The iterative methodology we used in the design and development of the learning environment, consists of a series of processes shown in Fig. 2 (Papadouris and Constantinou, 2009). The first process includes the formulation of learning objectives. These need to be a) consistent with students' conceptual and cognitive resources, and b) aligned with the conceptualisation of what is involved in learning in science. The second process draws on empirical investigations of students' initial understandings and difficulties regarding the specified learning objectives. The third process focuses on the development of the teaching/learning sequence, largely drawing on inputs from the previous two processes. The last process, which is also empirical in nature, includes the enactment of the designed teaching/learning sequence in classroom settings and the collection of data on students' learning outcomes. The findings from this field-testing are fed back to the design and development process so as to undertake refinements

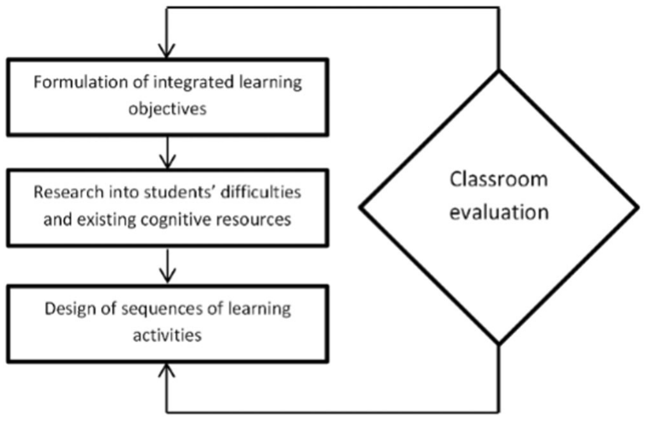

Fig. 2 The methodology employed in the design and development of the learning environment.

to the teaching design. This last process is vitally important - it allows for understanding how the designed 'learning materials' actually perform in the context in which they are intended.

The designed learning environment on 'Microbial Resistance to Antibiotics'.

Target audience. The microbial resistance learning environment is designed to address the needs of high school students. The phenomenon of microbial resistance is quite complex, drawing from different domains of biology, including physiology, immunology and microbiology, population genetics as well as chemistry. However, the learning environment could be adapted to a different age range by varying the breadth and depth of understanding that students are expected to attain. The designed learning environment is also suitable for use in teacher education. Pre-service teachers benefit additionally from such exposure by identifying and understanding the integration of innovative features in the design.

Addressing the principle of 'Science in Context'. The design principle of '*science in context*' was employed by framing the entire environment within the topical SSI of antimicrobial resistance. SSIs have been extensively used for contextualising learning environments. The prominent position they hold in science education is due to the suitable frames they offer for promoting scientific literacy for active citizenship (Hazelkorn et al., 2015). Working with SSIs presents a number of affordances for students. Firstly, making informed decisions on relevant issues is grounded in scientific evidence and understanding. Secondly, SSIs have a local dimension, which helps in relating to students' experiences but also extends beyond local, to national and global levels. Furthermore, SSIs provide a context for engaging students in cost-benefit analysis also requiring from them to bring together ideas from different domains, such as science, politics and economics, (Tal et al., 2011). Finally, the moral dimensions of these issues motivate students to engage in constructive discourse and enhance their need for augmenting their content knowledge (Zeidler and Nichols, 2009). Therefore, SSIs constitute an effective context for engaging students and keeping them motivated for the extended period of time needed for robust knowledge construction. Several educational researchers have reported that students engaging in discourse around SSIs show improved conceptual understanding (Klosterman and Sadler, 2010; Sadler, 2011; Theobald et al., 2015), informal reasoning (Sadler and Zeidler, 2005), reflective judgement (Zeidler et al., 2009; Liu et al.,

Table 1 Implementation of the design principles in the learning environment *Microbial Resistance to Antibiotics*.

Design Principle	Implementation
Integration of epistemic practices	Evaluation of evidence with emphasis on source credibility, accessible information about reliability/validity of methods and scientific authority. Coordinating the communication message with the expertise of the audience (doctors, pharmacists, general public).
Making evidence-based inferences	Developing an understanding of concepts related to (i) evolution and adaptation of micro-organisms; (ii) the body's response to infection; (iii) capacity for co-ordinate response to infection as a public health issue.
Competence-oriented design	Argumentation was prioritised as the competence under focus: using evidence to support claims and refute counter-claims. Connection with developing a credible information campaign that would be convincing for a specific target audience.
Authentic and relevant context	The socio-scientific issue of antimicrobial resistance with implications for public health and personal hygiene was selected.
Scaffolding for engagement and reflection	Driving mission: design an information campaign to increase awareness. Structured access to scientific data and digital tools to develop the targeted information campaigns. Facility for offering individualised and small group feedback on actual student work; facilitation of reflection through explicit phases of planning, monitoring and evaluation of own work. Hints and glossary provided practical assistance with conceptualisation and navigation.

2015), and argumentation skills (Jimenez-Aleixandre, 2002; Zohar and Nemet, 2002).

Sadler (2009; p.13), also recommends SSIs 'because they provide opportunities for students and teachers to engage with science in meaningful and relevant ways' and offer opportunities for students to understand and appreciate 'how science affects their lives and the lives of others' (p. 15).

The context topic of microbial resistance. Microbial resistance is the resistance of microorganisms to antimicrobial drugs that were originally effective for treating infections caused by them (WHO, 2014). However, the term is used more commonly to describe or refer to bacteria resistant to antibiotics. Resistant bacteria are created by random mutations or when resistant traits are exchanged between bacteria. In an antibiotic-rich environment, resistant bacteria are favoured by natural selection and thrive over time. Therefore, misuse and overuse of antibiotics and general antimicrobial agents create an environment that helps resistant microbes to emerge and prevail over sensitive ones. There is overwhelming evidence attesting to increasing use of antibiotics, including through over-prescription and overconsumption, leading to an increasing prevalence of resistant bugs (Morrison and Zembower, 2020; van de Sande-Bruinsma et al., 2008). Overconsumption and misuse of antimicrobials by the general public are due to false beliefs regarding infections and antimicrobial agents. Thus, a vital step toward the containment of microbial resistance is education (Sosa et al., 2010; WHO, 2001). Part of educating the lay public is educating students to be in a position to make informed decisions about the use of antibiotics.

Despite the fact that microbial resistance attracts significant attention in the health industry, often due to persistent strains of resistant bacteria turning up in hospitals, a substantial percentage of the general public is unaware of this issue. It is important that students are informed and helped to understand the need to safeguard against infectious disease and to appreciate the importance of efforts extend the longevity of existing antibiotics and discover new ones.

Addressing the principles of integrating epistemic and social practices. In our learning environment students were engaged in rhetorical argumentation. Working in groups for the full duration of the intervention, they had to co-construct valid arguments supporting their standpoints. Argumentation entails the ability to formulate and evaluate claims. In the intervention, students first learn how to construct sound arguments and after they have accrued the required knowledge and skills, they proceed to evaluate arguments constructed by their peers. The learning objectives and the pacing of activities for the development of argumentation skills emerged by combining theoretical knowledge on formulating and evaluating arguments and associate students' difficulties as presented in the research literature.

The learning environment examines the complex SSI of microbial resistance and aims to successfully combine and promote the development of a) argumentation skills and b) conceptual understanding of concepts pertaining to the topic of microbial resistance.

Conceptually, our main priority was for students to acknowledge microbial resistance as a natural selection process and develop understanding of the basic evolution mechanisms. Evolution is a core idea in the Life Sciences. Students have great difficulty understanding both evolution (Neubrand and Harms, 2017, Archila and Molina, 2020) and microbial resistance (Fonseca et al., 2012; Richard et al., 2017). The 'example' of microbial resistance is conducive to promoting students' understanding due to the fast generation times of bacteria and the relevance of the SSI to public health. The implementation of the design principles in the learning environment *Microbial Resistance to Antibiotics* is shown in Table 1.

Apart from evolution, for students to develop a coherent conception of microbial resistance, it was important to differentiate between the main types of microbes causing infections, to recognise the important and beneficial role of certain bacteria, viruses (eg. Bacteriophage) and fungi, to understand the human body's defence mechanisms (immune system), and the main types of microbial medication available for fighting infections. The learning environment included information and structured activities on all these issues.

Description of the learning environment. The microbial resistance learning environment was developed in STOCHASMOS (Kyza and Constantinou, 2007), a web-based platform designed to promote enquiry-based learning. The STOCHASMOS platform is organised into two main parts: the Inquiry Environment and the Reflective Workspace. The Inquiry Environment contains all the information that students are given access to in relation to the issue/problem under study. In the Reflective Workspace the designers create templates, which help students gather and synthesise important information to attain the learning objectives. The Reflective Workspace is used by the students as a co-creation environment to collaboratively develop their project in response to the driving question or the mission declared from the start. Following is a description of the Inquiry Environment and

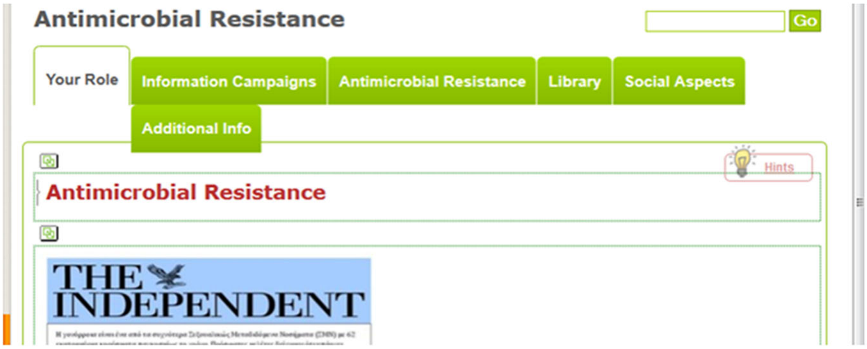

Fig. 3 Image of the online Inquiry Environment on Microbial Resistance.

Reflective Workspace with reference to the design principles presented in the first section of this paper.

Our first design principle has been embodied in the learning environment by scaffolding the development of conceptual understanding and argumentation competence in unison. Typically, scientific literacy in schools is restricted to scientific ideas and concepts which are presented as separable and unambiguous facts, stripped from their context, often as the work of a single individual. Argumentation activities engage students in collaborative discourse and constructive criticism, during the consensus-building process, which resembles the practices scientists follow for the justification and verification of scientific knowledge. Contemporary views of science learning manifest the integration of conceptual understanding with other significant components of science learning, such as argumentation. The following paragraphs exemplify the way conceptual understanding and argumentation were integrated into the Inquiry Environment, as well as the remaining design principles presented in the first section, through the unfolding of the learning environment.

The first dimension *Taking a Role* (Fig. 3) of the Inquiry Environment introduces the microbial resistance issue through newspaper clippings and presents the students' mission, which is to co-design communication products (posters, brochures and short videos) aiming to inform the lay public and stakeholders (doctors, pharmacists, nursing and other medical personnel) on the issue of microbial resistance. In addition to contextualising the learning environment with the SSI of microbial resistance, a scenario was used to enhance students' motivation. In the framing scenario, students undertake the role of employees at a communication firm, who work in design teams to develop an awareness campaign to raise public awareness and engage health professionals in taking a more active role in pre-empting the issue of microbial resistance and mitigating its implications for public health. The students' mission was formulated to facilitate co-creation and to maintain their interest for the extended period of time required to attain understanding of microbial resistance and to learn to formulate robust and well-supported arguments.

The second dimension, '*Information Campaigns*', includes guidelines that help students develop an effective awareness campaign. Particular emphasis was placed on how to adapt their approach and content according to the target audience: lay public and stakeholders, including health professionals. This dimension also incorporates explicit teaching/learning activities for cultivating argumentation skills.

The '*Microbial Resistance*' dimension scaffolds students to build an initial understanding of the issue of microbial resistance and to recognise the need for raising public awareness, thus giving 'true' purpose and meaning to the mission. The importance of this major public health issue is manifest through the presentation of authentic evidence, including data from public health monitoring websites showing the increasing detection of antibiotic resistant microbes around the world, interviews from the scientific community, patients and the general public. After students have covered the argumentation explicit activities, they are in a better position to recognise, appreciate and assess the value of various types of evidence portrayed under this section and the rest of the learning environment. Students have to evaluate the evidence while in the process of formulating their final arguments that underpin their campaign messages.

The '*Library*' dimension encloses all the background information needed by the students to develop deep understanding of the biological phenomenon of microbial resistance. The Library covers the following concepts: microorganisms and infections, the immune system, evolution and natural selection, and the function of antibiotics. The scope of this dimension is not to get students to develop deep conceptual understanding on each of the individual concepts covered in the various sections (sub-tabs) of this dimension. Instead, the Library provides a more elaborative overview of these concepts to assist students in formulating a complete picture of microbial resistance and select what information is more relevant for their mission and delve more deeply into it. This dimension interweaves conceptual understanding and argumentation skills by providing students with biological facts that can be employed as pieces of data (evidence) in their arguments. More significantly, students develop their reasoning by conceptualising the causal mechanisms that create and feed the predominance of resistant bacteria. To scientifically warrant their claims, students have to come to terms with fundamental concepts covered in the Library.

The fifth dimension, '*Social Aspects*', focuses on various erroneous behaviours of both target groups (lay public and public health stakeholders) at a national and international level, such as antibiotic consumption for the production of food products, over-prescription, overconsumption and inappropriate storage of antibiotics. The dimension also contains real data in diverse formats (e.g. text, graphs, tables) that illustrate the increasing trends in antibiotic consumption. Students are encouraged to use the platform tools to manipulate and interpret the supplied data to reach conclusions regarding a range of issues in relation to microbial resistance, such as exploring connections between the increasing trend in antibiotic consumption and the increasing percentages of multi-resistant bacteria, or other social and economic ramifications of microbial resistance. The final section (sub-tab) of this dimension is entitled '*Science and Technology*'. Through the design, development and the mass production stages of antibiotic development, students come to realise the interconnection and interrelationships between scientific research and technological development.

The learning environment is designed in such a way that students can go back and forth between the various dimensions

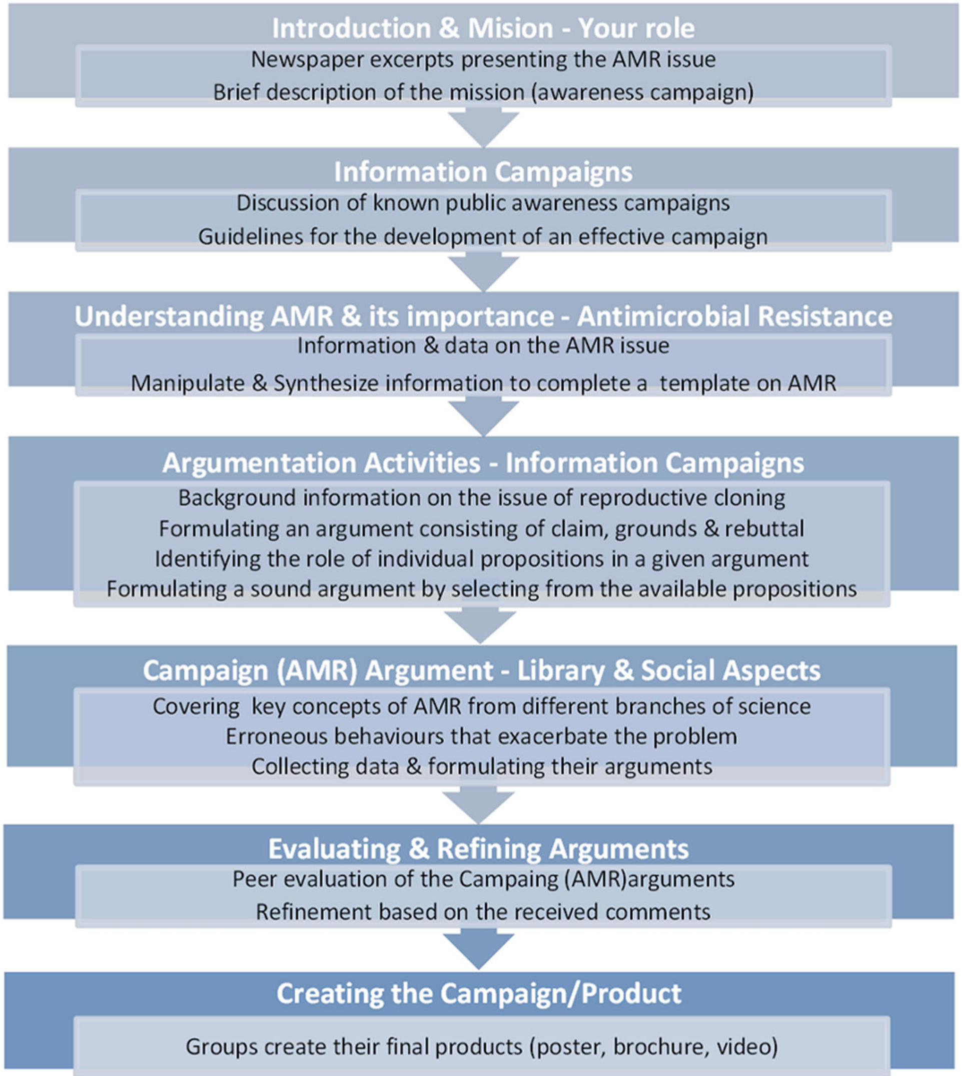

Fig. 4 Activity Sequence embedded in the Learning Environment.

and cross-reference their working hypotheses and their arguments as they are being developed. By undertaking the mission to develop an awareness campaign students are encouraged to work through the first three dimensions in an almost sequential manner. This is supported by the fact that the dimensions have been sequenced in a way that responds to the challenge at hand: what are the main steps in developing an effective campaign? Why is an awareness campaign on microbial resistance necessary? What arguments can be developed to support the information that will go out to different stakeholder groups? Normally, the subsection enclosing the argumentation activities is not made available to students until they have covered the introductory section on '*Microbial Resistance*'. This is intended to safeguard that students have developed a grasp of the basic ideas before they engage with the process of formulating claims and evaluating what evidence is relevant to their claims and how can it be used to support each claim.

Regarding the '*Library*' dimension, students become engaged in collaborative activities that cover every section before moving to the next. The intended purpose is for students to grapple with concepts in a sequence that facilitates understanding and also encourages connections. For example, students can better understand the defence mechanisms our immune system has in place for the different 'enemies', after they learn to identify a few key characteristics of the various types of microbes. After students have covered the '*Library*' dimension and have gained information on how to formulate structurally complete (based on Toulmin's model) and valid arguments, they move freely back and forth guided by their mission, in efforts to construct concise and robust arguments for their awareness campaigns. An overview of the activity sequence for the entire learning environment is presented in Fig. 4.

Argumentation activities. To nurture the argumentation competence, we designed an initial set of activities for explicit teaching of the structural features and quality characteristics of an argument, followed by exploratory enquiry activities with embedded peer-assessment. To encourage students to appreciate the value of '*making evidence-based inferences*', we included multiple opportunities to discuss the distinct epistemological features of evidence and explanations (data and warrants using Toulmin's terminology) and to formulate or review evidence-based arguments. We also discussed explicitly the 'value' of internal consistency in the reasoning that connects evidence to claim.

The argumentation activities also place emphasis on structure, following Toulmin's model (1958), as well as the quality of the argument, by stressing the relative value of various types of evidence, the need for scientifically accepted explanations to link evidence to claim, and the coherence and cohesion of the argument as a whole.

Students are assessed and given feedback on the different elements of a robust argument and the quality aspects using a different SSI, that of reproductive cloning. The aim is for students to attempt transfer of what they have learned from the context of cloning to the context of cloning to the context of microbial resistance. It is important to stress here that the information on reproductive cloning were made available to students through the Inquiry Environment but the first two activities were developed in the Reflective Workspace of the STOCHAMOS platform.

The introductory activity was the formulation of an argument including all the essential/main structural components (claim, data, warrant), as well as rebuttal. Students studied all the relevant information and watched two short documentaries on the subject of cloning and then had to complete a template where the questions guided them to state their claim and provide evidence supporting it. Following this, students had to think as someone holding an opposing position and provide supporting evidence and then to challenge those evidence. The second activity was based on a template providing an argument against reproductive cloning and students were asked to identify the function/role of the individual propositions. The final activity was prompting students to formulate the strongest argument possible by selecting from the available choices of individual propositions. For each structural component, students were given two options and according to their previous selection, one of the propositions was qualitatively stronger. After completing the task students had to compare their arguments with the one formulated according to the teacher's selection and discuss advantages and disadvantages of their choices. Once students had completed those argumentation activities, explaining explicitly a robust argument's structure and content, they had to construct their own sound argument on the issue of microbial resistance and evaluate an argument created by their peers.

Scaffolding used in the learning environment

Inquiry environment scaffolding. To support students in their endeavour in the Inquiry Environment two scaffolding tools embedded in STOCHASMOS platform were utilised, hints and glossary. The glossary helps students to sustain focus in their activities without being distracted by difficult terminology. When a term has been entered in the glossary database of the environment, the word appears in the text with a green colour and upon mouseover the definition appears on a pop-up window. Hints were provided in the learning environment for two purposes: a) to direct students' attention on specific sections that were important for completing their mission and b) to provide explanations for concepts or phenomena. For example, while students were working on the argumentation activities on the provided information, the terms gene and genome emerged. Genetic concepts are usually confusing to students (Smith et al., 2008) and contrasting the two terms might enable students to distinguish them. Moreover, different representation formats were employed to support students; particularly useful was the embedment of multimedia representations. In biology where we are dealing with abstract concepts and phenomena it is important to connect verbal description with a picture, or even better, with a multimedia representation. According to Yarden and Yarden (2013, p. 95) multimedia representations 'are most likely to lead to meaningful learning'.

In the learning environment, a blended approach was used regarding scaffolding. Hence software scaffolding co-existed with teacher-enhanced scaffolding or human support (Lund, 2004). In pre-determined points of the Inquiry Environment, students were directed to discuss with one of the members of the teaching staff. The interaction of the staff with the students was based on the Socratic method. During the semi-Socratic discussions, students acquired knowledge was used to advance their understanding. Students' engagement with this type of discourse, where they are not given answers but are guided through questions to reach to the next level of understanding, helps them process information and improves their thinking and reasoning skills.

Workspace scaffolding. All the environments hosted in the STOCHASMOS platform incorporate the Reflective Workspace Environment. In the Workspace, using pre-designed templates, students gather and synthesise data from the Inquiry Environment. The templates provide scaffolding to students in selecting appropriate data and to synthesise them according to the requirements of the task. In the Microbial Resistance Learning environment, six template pages were created and used by the students; three pages were devoted to argumentation, two pages to microbial resistance and one page was for the construction of the awareness campaign.

The argumentation template pages are sequencing the development of argumentation skills (see 3.3.4. Argumentation Activities). The first template guides students in a step-by-step process to formulate arguments comprising the main elements of Toulmin's model. The second template support students in comprehending the different role and epistemology of the main elements and the final template engages students in peer-discourse and teacher-discourse, in their groups, by juxtaposing two arguments, one formulated by them and the other by the teacher. This template examines both vital aspects in constructing robust arguments, structure and quality of the individual elements. In all three template pages there are discussions taking place to improve students' epistemologies of what counts as good evidence (data) and good explanations (warrants).

Regarding the microbial resistance templates, these focused on enhancing students' understanding on microbial resistance as a SSI and as a biological phenomenon based on natural selection. The last template supported students in formulating the argument that would constitute their awareness campaign. The template helped students to collect and organise their data and then to formulate an argument congruent to Toulmin's model. This template was also used to scaffold peer-discourse between the groups. The groups were paired and exchanged their templates. Students had to evaluate each other's arguments based on three criteria: structure, content and language adaptation according to the target audience, and quality of the content. Criteria were given to students in a checklist format to help them provide their peers with constructive feedback.

The Reflective Workspace environment was designed to scaffold ongoing reflection. When learning materials are contextualised with complex authentic problems, students need additional support to meet our expectations. Students need support to collect and organise data, to synthesise findings, and to determine how to proceed. By articulating their thinking in the pre-designed templates, students reflect on their progress; what has been understood and what needs revising. Reflection was also supported by the structured discussions, organised around the templates, with the teacher.

Discussion

This study focused on the design and development of an online enquiry-based environment on the topical socio-scientific issue of microbial resistance to antibiotics. Emphasis was given on the design principles embedded in the learning environment which emerged from research focusing on promoting enquiry learning in order to change the way science is taught in schools. This study exemplified the following design principles: *science in context*, integration of *epistemic practices*, *evidence based-inferences, competence-oriented design* and *scaffolding for student engagement and reflection*. These design principles were adopted and adapted from existing literature in designing curriculum materials and learning environments in the subject of science.

The way the design principles have been presented at the beginning of the article seeks to provide, aspiring designers of learning materials, with basic tenets that could be modified to fit their purposes. Hence, the description of each tenet starts by revealing the reasons behind the selection, what we were trying to accomplish and why this is important regarding our knowledge on how students learn and the challenges (barriers) that impede their learning. Following this, there is an overview of how it was exemplified in the learning environment. In the description of the learning environment it becomes more apparent how each principle was adapted and applied in the design. Therefore, one of the aims of the article is to support teachers and other educators that undertake the task of designing activities and learning sequences to elicit certain features that would benefit their teaching practice and also to reflect on their own designs and how to evaluate them.

Furthermore, it is important to stress here the significant role the enactment of the learning material and the school and classroom settings have in the achievement of the learning outcomes. Enquiry-based learning needs to be also facilitated by the classroom culture. Students need to learn to collaborate, to exchange ideas and to construct on each other's knowledge. To transform classroom culture demands a radical change in the role the teacher adopts in the classroom and the teaching approaches. The teacher needs to act as a guide, as a facilitator and as an equal member of the learning community of the classroom. Hence, reformed learning materials have to be accompanied by reformed classroom cultures (Reiser et al., 2001).

Regarding educational research, the article describes development of a learning environment that has innovative features and utilises a SSI that is at the forefront of the interests of the scientific community and public health policymakers and deserves wider public attention. The SSI of antimicrobial resistance, to our knowledge, has not been used as a context in a digital science learning environment. Examples of other socio-scientific topics that have been employed in the past as contexts for learning environments include, cloning, genetically modified organisms, global warming and other environmental and ecological issues. Furthermore, following the designed principles presented here, we developed an environment that is in accordance with the conceptual framework proposed by the National Research Council Committee (NRC, 2012). The proposed framework comprises three dimensions, practices, cross-cutting concepts and core ideas in the science disciplines that need to be woven together to facilitate students' learning (NRC, 2012, p. 29). From the major practices included in the NRC report, the microbial resistance learning environment promotes the development of the argumentation competence. Also, in the context of microbial resistance, students cover the core idea of evolutionary adaptation of microbes. The combination of formulating arguments and the framing issue of microbial resistance engage students in exploring causal relationships, which is one of the crosscutting concepts identified in current educational policy priorities.

Data availability

No data were generated or analysed for the purposes of the work reported in this article. The article describes the principles for creating a digital learning environment and how they were enacted in a platform for supporting reflective enquiry in science. Hence data sharing is not applicable to this research.

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Author contributions

CC initiated the formulation of the design principles and set the frame for the design enactment. CC and ER contributed to the elaboration of the ideas and the writing of the manuscript. The authors of this study participated voluntarily, collectively contributing to the conception of the main ideas and the writing process. This collaborative effort underscores the shared commitment to advancing our understanding of digital learning environments and their purposeful design for enhancing meaningful interactions and the quality of educational experiences.

Competing interests

The authors declare no competing interests.

Ethical approval

This study did not involve human participants, their data or any form of biological material. Hence no ethical approval was required to conduct this research.

Informed consent

This article does not contain any studies with human participants performed by any of the authors.

Additional information

Correspondence and requests for materials should be addressed to Constantinos P. Constantinou.