Routledge
Taylor & Francis Group

Journal of Biological Education

ISSN: 0021-9266 (Print) 2157-6009 (Online) Journal homepage: https://www.tandfonline.com/loi/rjbe20

Promoting RRI and active citizenship in an inquiry-based controversial socio-scientific issue: the case of cholesterol regulation with statins

Andreas Ch. Hadjichambis, Yiannis Georgiou, Demetra Paraskeva Hadjichambi, Eleni A. Kyza, Andria Agesilaou & Demetrios Mappouras

To cite this article: Andreas Ch. Hadjichambis, Yiannis Georgiou, Demetra Paraskeva Hadjichambi, Eleni A. Kyza, Andria Agesilaou & Demetrios Mappouras (2019) Promoting RRI and active citizenship in an inquiry-based controversial socio-scientific issue: the case of cholesterol regulation with statins, Journal of Biological Education, 53:5, 548-560, DOI: 10.1080/00219266.2018.1530277

To link to this article: https://doi.org/10.1080/00219266.2018.1530277

JOURNAL OF BIOLOGICAL EDUCATION
2019, VOL. 53, NO. 5, 548–560
https://doi.org/10.1080/00219266.2018.1530277

Routledge
Taylor & Francis Group

Promoting RRI and active citizenship in an inquiry-based controversial socio-scientific issue: the case of cholesterol regulation with statins

Andreas Ch. Hadjichambis[a,b,c], Yiannis Georgiou[c], Demetra Paraskeva Hadjichambi[a,b], Eleni A. Kyza[c], Andria Agesilaou[c] and Demetrios Mappouras[a]

[a]Biology - Secondary Education Department, Cyprus Ministry of Education and Culture, Nicosia, Cyprus; [b]Cyprus Center for Environmental Research and Education, Lemesos, Cyprus; [c]Department of Communication and Internet Studies, Cyprus University of Technology, Lemesos, Cyprus

ABSTRACT

Science education is an important dimension of the European Commission's Responsible Research and Innovation (RRI) objectives; however, RRI is not an explicit focus of biology teaching and few biology teachers have experience in integrating RRI in classroom practice. This study examines the impact of a three 80-minute RRI and active citizenship module on 11th grade biology students, based on the SSIBL pedagogical framework. A representative national sample of 11th grade biology students in Cyprus (n = 398) participated. A pre-post research design examined impact in relation to students' conceptual understanding regarding cholesterol and its regulation, their understanding of the controversy about cholesterol regulation, awareness of RRI components, feeling of responsibility and willingness to act. Analyses indicated statistically significant gains in conceptual understanding and the understanding of the controversy about cholesterol regulation and awareness of RRI components, as well as in students' socio-scientific accountability (feeling of responsibility and willingness to act). Conceptual understanding showed increased correlations with Controversy understanding and RRI understanding forming the three of them the cognitive elements of individuals understanding. All of the examined variables are deemed, as of great importance for the design, implementation and evaluation of innovative biology RRI and active citizenship modules.

KEYWORDS

Responsible Research and Innovation (RRI); active citizenship; controversial socio-scientific issues; inquiry-based learning; conceptual understanding; biology education

1. Introduction

Supporting students in understanding how scientific research and technological innovation have changed, and how they shape our world is of great importance (Blumenfeld et al., 2000). Many of these changes have a positive impact on the quality of our lives; however, others create new risks, controversies and ethical dilemmas, and are not always successful in solving the problems they meant to address. Therefore, science education, and biology education specifically, has an important role to play in helping students develop the skills needed for making sense of controversial Socio-Scientific Issues (SSIs), such as genetically modified foods or nanotechnology products, and taking informed, evidence-based and responsible decisions.

CONTACT Andreas Ch. Hadjichambis a.chadjihambi@cytanet.com.cy
Supplemental data for this article can be accessed here.

The use of statins for cholesterol regulation is one such controversial SSI. According to a series of research studies, statins seem to have beneficial effects in reducing mortality in patients with cardiovascular disease, which is one of the main causes of death and disability in the Western world (American Heart Association, 2008; Strippoli et al., 2008). Therefore, a strong argument can be made that statins are important in the secondary prevention of cardiovascular disease (Brugts et al., 2009). However, evidence from other studies report several statin-associated side effects, such as cognitive loss, neuropathy, muscle adverse effects, pancreatic and hepatic dysfunction, and sexual dysfunction (Golomb and Evans, 2008). Therefore, the use of statins, as a drug for lowering cholesterol in human blood, remains a controversial issue among scientists and the broader society due to insufficient evidence being available to resolve the scientific question, and also due to a finely-balanced cost-benefit analysis where individuals might legitimately hold different opinions.

Despite the significance of this controversial SSI, there is currently lack of learning interventions addressing this topic. This study evaluates the effectiveness of a module, which is grounded on the controversial SSI of regulating cholesterol through statins, for promoting active citizenship as well as Responsible Research and Innovation (RRI) in high school biology, seen through the lens of the Socio-Scientific Inquiry Based Learning (SSIBL) pedagogical framework (Levinson, 2017b). Based on the review of the literature, the investigation of RRI and active citizenship learning interventions are under-researched topics, and thus, the contribution of the present study will enhance the current understanding of the value and affordances of such interventions in high school biology.

2. Theoretical background

Controversial SSIs, like cholesterol regulation through statins, have been argued to provide powerful learning contexts; they can support the development of students' scientific literacy, argumentation practices, and critical thinking, while also motivating students to learn science due to the authentic nature of the topic and the relevance to students' personal lives (Zeidler and Nichols, 2009). Teaching using SSIs can prompt students to adopt more responsible citizenship roles within the society (Eilks & Feierabend, 2010) and can help them connect abstract scientific knowledge to real life (Christenson, Rundgren & Höglund, 2011).

An emergent notion in context of teaching using SSIs is the notion of RRI which constitutes the main principles for socially desirable, ethically acceptable and sustainable development in the fields of science and technology (Levinson and PARRISE consortium 2017a), such as for instance the development of statins for the regulation of cholesterol. According to the European Commission (EC), 'Responsible research and innovation is an approach that anticipates and assesses potential implications and societal expectations with regard to research and innovation, with the aim to foster the design of inclusive and sustainable research and innovation.' (European Commission, 2017). RRI is grounded on the notion that technological and scientific progress is the basis for a better future. However, innovations must be carefully planned, if they are to address societal needs in accordance to widely-agreed upon values, while also maximizing the benefits and reducing harmful impact. Science Education, is the third dimension of RRI, according to the European Commision, as science education is making the language and tools of science available to everyone (European Commision, 2017).

Extending the traditional teaching of SSIs, in terms of understanding, mapping and deconstructing complex socio-scientific controversies, RRI emphasizes also the importance of preparing young students, the future citizens, in order to be able to actively involved, as equal stakeholders, in the process of the scientific and technological evolution, which is observed nowadays. In particular, RRI emphasizes the need to concurrently develop an understanding of the scientific concepts but also to critically examine the social and ethical dimensions of these concepts (Heras and Ruiz-Mallén, 2017). As such, a well-structured RRI learning module should primarily have the affordances to contribute to the promotion of students' active and responsible citizenship, as

this is reflected in the development of students' socio-scientific accountability, on top of facilitating students' content knowledge and understanding of complex socio-scientific issues.

2.1. Teaching SSIs and content knowledge

When teaching a controversial SSI, science knowledge has been regarded as content knowledge (Klosterman and Sadler, 2010). In this context, content knowledge has been defined as the conceptual understanding of scientific concepts and principles, which are aptly related to nature of the socio-scientific controversy (Kolstø et al., 2006; Sadler and Fowler, 2006). While SSI-oriented learning modules have been often argued to contribute to the development of both students' conceptual understanding and understanding of the SSI controversy, there has been a disagreement when it comes to the relationship between conceptual understanding and understanding of the SSI. As captured by Jho, Yoon, and Kim (2014) while some studies have reported that there is significant relationship between students' conceptual understanding and understanding of complex SSIs, other studies reported that students' conceptual understanding is more or less independent of the way students conceptualize complex SSIs and support their decisions on these controversial topics. These relationships maybe even more complicated but still uncharted in the context of RRI learning modules that attempt to contribute also to the development of students' socio-scientific accountability.

2.2 Socio-scientific accountability

According, to Cross and Price (1999), responsibility is one of the fundamental elements that people should strive to achieve in contemporary society. The feeling of responsibility can be defined as the feeling that people are liable for creating and/or resolving controversial SSIs; thus, people take actions to promote their decisions (Lee et al., 2013). In addition, according to the same authors, it includes a belief that even small actions are useful at resolving a controversial SSI. This is very important especially on issues that are more personal, such as cholesterol regulation in order to reach a personal decision. On the other hand, willingness to act refers to a personal commitment to address and actively contribute to resolve a controversial SSI in a broader context beyond the personal decision (Lee et al., 2013). This attribute is often regarded as a powerful predictor of realizing socio-political actions throughout life (Boyes, Skamp, and Stanistreet, 2009; Kaiser, Wolfing, and Fuhrer, 1999). In the case of cholesterol regulation an example include the action to inform others such as the school mates, parents, teachers. Both, the feeling of responsibility and willingness to act are essential components in forming socio-scientific accountability (Lee et al., 2013).

Socio-scientific accountability implies that someone is responsible for the consequences of a decision or action, while responsibility carries with it the personal acceptance for those outcomes and courses of action. As such, the notion of socio-scientific accountability seems to compose a major component of RRI which highlights the need to prepare young students, in order to be able to involve as active citizens and equal stakeholders in the process of dealing with complex SSIs. However, the integration of RRI and active citizenship modules into teaching is a complicated matter (de Vocht, Laherto, and Parchmann, 2017). According to the same authors teachers voiced personal concerns about their ability to teach RRI, and need extended support and networking to contextualise RRI into their science lessons. In addition, given that RRI in education is still in its infancy, there is a general lack of RRI learning modules in biology education and the publication of relevant examples will enrich teachers with ideas on how to approach it.

3. Rationale

The purpose of this study is twofold. First, the goal of this study is to evaluate the effectiveness of an RRI and active citizenship module about cholesterol regulation and statins, in relation to students' conceptual understanding, to students' understanding of the controversy about

cholesterol regulation, as well as to students' awareness of RRI components, and socio-scientific accountability (in terms of feeling of responsibility and willingness to act). Second, this study aims to investigate the relationship between the aforementioned potential learning gains.

These goals are captured in the following research questions:

- What is the impact of the RRI and active citizenship learning module on students' conceptual understanding and their understanding of the controversy about cholesterol regulation with statins?
- What is the impact of the RRI and active citizenship module on students' awareness of RRI components?
- What is the impact of the RRI and active citizenship module on students' socio-scientific accountability (feeling of responsibility and willingness to act)?
- Is there a relationship between students' conceptual understanding, awareness of RRI components, and socio-scientific accountability (feeling of responsibility and willingness to act)?

4. Methodology

This study adopted a quasi-experimental methodology, employing a pre- and post-test research design. The following sections present the methodology of the study – the sample, the educational intervention, the research tools, the data collection and data analysis methods –, to provide the reader with an overview of the research design.

4.1. Sample

The participants in this study were 462 Greek-speaking 11th graders (16–17 years old) in Cyprus, from 11 public high schools; the sample of this study was selected according to the method of random stratified sampling. Sixty-four students were removed from the final sample due to not completing the pre- or the post-test. The final sample was 398 students, comprised of 261 girls (65.6%) and 137 boys (34.4%), from 28 classrooms, taught by 22 biology teachers. Students were of mixed academic ability according to the national educational practices, each classroom included students whose cognitive abilities ranged from high-average to low-average, as well as some highly-gifted students. Overall, the classrooms' structure in combination to the random stratified sampling ensured that there were no significant differences between the various classrooms and that the sample was representative of the broader student population, respectively. An overview of the final sample is presented at Table 1.

4.2. Learning intervention

The RRI and active citizenship module, which was enacted in the context of this study, was entitled 'How to control your cholesterol: through statins or through exercise and nutrition' and was developed by seven in-service biology teachers through a collaborative and participatory design approach. The biology teachers co-designed the module, during their participation in the [*not named for blind review*] professional development program, according to the Socio-Scientific Inquiry-based Learning (SSIBL) pedagogical framework (Figure 1).

4.2.1. The RRI active citizenship module design framework

The RRI and active citizenship learning module, which was a three-lesson module with each lesson lasting 80 minutes, was designed and applied in four phases. In the first phase, an authentic scenario was designed that lays the foundation for the examination of the controversial SSI. In the second phase, a sequence of inquiry activities was designed aiming to enable students to acquire conceptual understanding of the topic related to the module, as well as develop their inquiry skills

Table 1. Overview of the final sample.

Schools	Teachers	Classrooms	Students
School 1	Teacher 1	Classroom 1	12
	Teacher 2a	Classroom 2	11
		Classroom 3	16
School 2	Teacher 3	Classroom 4	11
	Teacher 4	Classroom 5	15
School 3	Teacher 5	Classroom 6	14
		Classroom 7	11
School 4	Teacher 6	Classroom 8	17
		Classroom 9	17
School 5	Teacher 7	Classroom 10	17
		Classroom 11	20
		Classroom 12	20
		Classroom 13	16
School 6	Teacher 8	Classroom 14	12
School 7	Teacher 9a	Classroom 15	13
	Teacher 10	Classroom 16	15
	Teacher 11	Classroom 17	13
School 8	Teacher 12	Classroom 18	10
	Teacher 13	Classroom 19	10
		Classroom 20	16
School 9	Teacher 14	Classroom 21	16
	Teacher 15	Classroom 22	19
School 10	Teacher 17a	Classroom 23	10
	Teacher 18	Classroom 24	16
	Teacher 19	Classroom 25	12
School 11	Teacher 20	Classroom 26	6
	Teacher 21	Classroom 27	17
	Teacher 22	Classroom 28	16

aMarked with an asterisk are three of the biology teachers, who also participated in the development of the learning intervention [See next section].

(e.g. collection, organization, analysis and interpretation of data, reasoning skills). In the third phase, the designed activities supported students in taking an informed decision based on the available evidence. Finally, in the fourth phase, through the designed activities students were asked to undertake both individual and collective citizenship actions (Figure 2). This framework can be applied not only in the specific module regarding regulating cholesterol using statins but also in other biology modules which seek to promote the RRI and active citizenship.

4.2.2. Phase 1: introducing the controversial SSI

According to the learning scenario, a short video produced by the co-design teachers, Peter, a high school student, is called to the office of the assistant high school director, who informs him that his father had an important health problem and was unexpectedly hospitalized. At the hospital, Peter meets his mother and is informed that his father suffered a heart attack. Subsequently, the doctor advises the whole family to conduct general health examinations. Test results reveal that, besides his father, both Peter and his mother have high blood cholesterol levels.

Students were assigned with a multi-level mission; they were asked to help Peter to propose how to regulate his and his family's cholesterol levels. The driving question of students' inquiry was 'How to control your cholesterol: through statins or through exercise and nutrition?'. Students were also asked to prepare and share a YouTube video or an informative brochure for their fellow students and their families, as well as to organize a debate for the pros and cons of statin use for cholesterol regulation, inviting as audience their teachers, parents and relevant stakeholders.

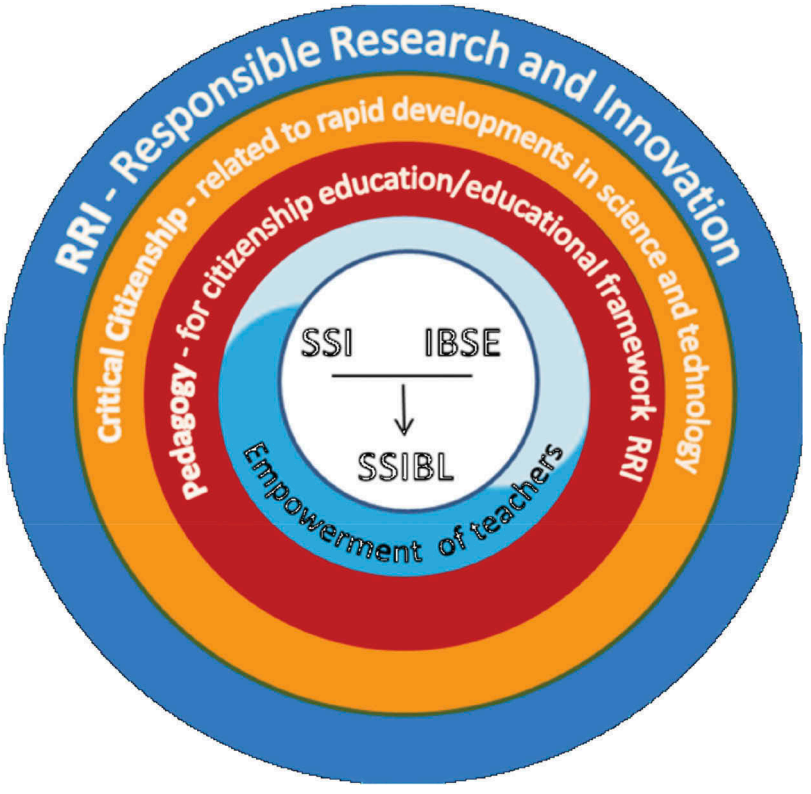

Figure 1. The SSIBL pedagogical framework.

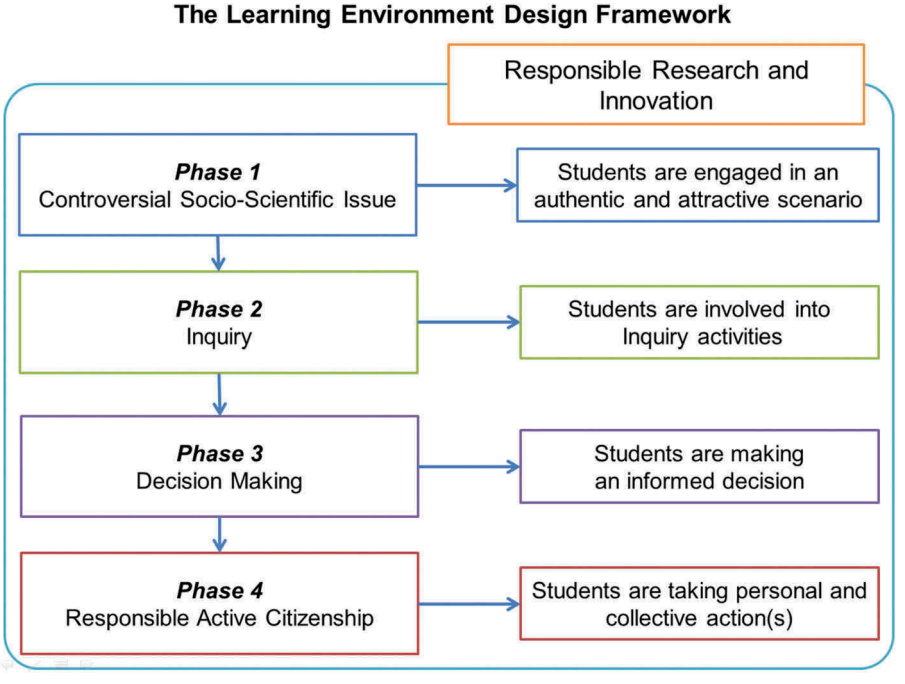

Figure 2. The design framework of the RRI and active citizenship module for Cholesterol-Statins.

4.2.3. Phase 2: inquiry

During this phase, students worked in four groups of 4–6 members. Each group was provided with both printed and digital information, such as videos and worksheets, and were asked to engage in small-scale investigations about the following sub-units: (a) Cholesterol: Structure and function; (b) Cholesterol and fat absorption; (c) Cholesterol and heredity; (d) Cholesterol and enzymes; (e) Cholesterol and atherosclerotic plaque; and (f) Statins and their function.

As students investigated these sub-units, they were also asked to collect and interpret data to take an evidence-based stance towards the controversial SSI. As part of this process they investigated different sources such as medical articles, modified for the age of students, patient interviews, nutritionists' websites and brochures, as well as gymnasts' and personal trainers' views and opinions. At the same time, they were asked to judge the reliability of these sources. The sources were all selected carefully and modified by the co-design teachers in order to reflect the point of view of each stakeholder, present scientific evidence and at the same time being appropriate for students' level.

4.2.4. Phase 3: personal and group decision

At the beginning of this phase the driving question 'How to control your cholesterol: through statins or through exercise and nutrition?' is addressed again. During this phase students were asked to make an informed decision based on the available data sources (such as videos, scientific articles, webpages, leaflets) and to discuss their personal decision with their peers in order to come up with a collectively justified decision realizing the difficulties to come up to a consensus collectively agreed.

4.2.5. Phase 4: active citizenship

During the active citizenship phase, in contrast to a traditional inquiry-based intervention, students were asked to suggest individual (e.g. inform others, send a letter) and collective citizenship (e.g. lobbying, organising a debate) actions in relation to the controversial SSI of using statins to regulate cholesterol. Furthermore, they considered the importance and the role of science for resolving such controversial SSIs; they critically examined the case of Dr. X, who concealed data to protect the interests of pharmaceutical companies; they defined the characteristics that should distinguish a responsible scientist; while they also prepared a motion towards the Ethics Committee about the ethical standards of medical researchers and doctors. The intervention concludes with a forty-minute debate during which the students were divided in two groups: the supporters and the opponents of using statins for regulating cholesterol. The debate was an open event in which teachers, parents and relevant stakeholders were invited. The aim of the debate was to engage the society in the controversial SSI and to inform others regarding the pros and cons of using statins to regulate cholesterol.

4.3. Data collection instruments

Two data collection instruments were employed, before and after the teaching intervention. The first instrument was a multiple-choice, conceptual assessment test. The test was composed of twenty items, with each correct answer scored with one mark, for a total score of twenty points (See Appendix A). Thirteen of these items aimed at evaluating students' conceptual understanding of core biology concepts such as cholesterol regulation, statins, atherosclerotic plaque and cardiovascular system, etc. (e.g. *What is HDL?*); three of these items aimed at evaluating students' understanding of the specific controversial SSI (e.g. *What is the main argument of those who support the use of statins to regulate cholesterol in people with high cholesterol?*); the remaining four items evaluated students' awareness of RRI components, such as the responsibility and ethics of scientists (e.g. *What should a motion towards the Ethics Committee of the Medical Association include?*). The test was developed by two biological education experts, thus ensuring expert and

face validity. The Kuder and Richardson Formula 20 (KR20) of the pre-test and post-test was 0.68 and 0.81, respectively, indicating satisfactory reliability.

The second instrument evaluated students' socio-scientific accountability (feeling of responsibility and willingness to act) for active citizenship (See Appendix B). In particular, the *Socio-scientific accountability* scale from the *Character and Values as Global Citizens Assessment [CVGCA] instrument* (Lee et al., 2013) was used for the purposes of this study. The original scale is composed from two subscales and includes a total of 7 items: (a) Feeling of responsibility (3 items – e.g. *I believe a small action I take will be able to contribute to resolving socio-scientific controversies related to health issues*), and (b) Willingness to act (4 items – e.g. *I will make efforts to mount community movements and communicate with community members to resolve socio-scientific controversies related to health issues*).

All seven items were adapted and translated in Greek. According to the original questionnaire, Cronbach's alpha for *Feeling of responsibility* was 0.64, while for *Willingness to act* was 0.69. Cronbach's alpha for the translated and adapted scales employed in this study was satisfactory and equal to 0.74 for each one.

4.4. Data collection

The tests were administered to students before and after the learning intervention and were completed in the presence of their biology teacher, with a maximum allocated time of 40 minutes. All participating 11th graders took both tests.

4.5. Data analysis

The statistical analysis of the tests examined differences in pre- and post-test scores of students' conceptual understanding and understanding of the controversial SSI, as well as of students' awareness of RRI components and socio-scientific accountability. The Wilcoxon Signed Rank Test was used for the analyses, as the data did not follow a normal distribution (See Appendix for the distribution of students' answers per item). Finally, the relationships between students' conceptual understanding, understanding of the SSI controversy, awareness of RRI components and socio-scientific accountability were investigated through the Pearson correlation coefficient.

5. Findings

The main findings of this study are presented according to the research questions posed.

5.1. Conceptual understanding and understanding of the controversial SSI

A Wilcoxon signed-rank test examined whether the differences in student learning scores reached significance, in terms of conceptual understanding (Items A1-A13, Appendix) and understanding

Table 2. Descriptive statistics and wilcoxon signed-rank tests showing pre-post results of students' conceptual understanding and understanding of the controversial SSI.

	PRE-test		POST-test			
	Mean	SD	Mean	SD	Z	Gain (%)
Conceptual understanding	7.07	2.52	9.65	2.51	−14.24***	37
Understanding of controversial SSI	1.60	0.92	2.28	0.84	−10.20***	43

Note. *p < .05, ** p < .01. ***p < .001.

Table 3. Descriptive statistics and wilcoxon signed-rank tests for comparing pre- and post-tests students' socio-scientific accountability.

	PRE-test		POST-test			
	Mean	SD	Mean	SD	Z	Gain (%)
Willingness to act	3.34	1.68	4.93	1.74	−12.57***	48
Feeling of responsibility	10.42	3.55	14.57	3.83	−15.42***	40

Note. *p < .05, ** p < .01. ***p < .001.

Table 4. Intercorrelations between students' conceptual understanding, understanding of the controversial SSI, awareness of RRI components, and socio-scientific accountability.

Variables	1	2	3	4	5
1. Conceptual understanding	—				
2. Understanding of the controversial SSI	**.423****	—			
3. Awareness of RRI components	**.583****	**.420****	—		
4. Feeling of responsibility	.306**	.254**	.302**	—	
5. Willingness to act	.288**	.197**	.274**	**.555****	—

Note. *p < .05, ** p < .01. ***p < .001.

of controversial SSIs (Items A14-A16, Appendix). Results showed significant improvement in students' conceptual understanding (z = -14.24, p < .001) with gain 37%, as well as in students' understanding of the controversial SSI about using statins for regulating cholesterol (z = -10.20, p < .001) with gain 43%. More information is provided in Table 2.

5.2. Students' awareness of RRI components

A Wilcoxon signed-rank test examined whether the differences in student RRI awareness scores (Items A17-A20, Appendix) reached significance. Results showed significant improvement in students' awareness of RRI components (z = -10.68, p < .001), with a gain of 51%.

5.3. Students' socio-scientific accountability

A Wilcoxon signed-rank test examined whether the differences in student socio-scientific accountability scores, in terms of students' feeling of responsibility (Items B1-B3) and willingness to act (Items B4-B7), reached significance. In particular, results showed significant improvement in students' willingness to act (z = -12.57, p < .001) with an important gain of 48% as well as on the feeling of responsibility (z = -15.42, p < .001) with a gain of 40%. More information is provided in Table 3.

5.4. Relationship between students' conceptual understanding, understanding of the controversial SSI about cholesterol regulation, awareness of RRI components, and Socio-Scientific Accountability

Bivariate correlations between the five variables - conceptual understanding (Items A1-A13, Appendix)., understanding of the controversial SSI (Items A14-A16, Appendix)., awareness of RRI components (Items A17-A20, Appendix), feeling of responsibility (Items B1-B3, Appendix) and willingness to act (Items B4-B7, Appendix) - showed positive relationships among all the variables (Table 4). The strongest relationships were observed among students' *conceptual understanding* and *awareness of RRI components*, as well as among students' *willingness to act* and *feeling of responsibility* with moderate positive relationship. The *understanding of the controversial SSI* was related with a moderate positive relationship with *conceptual understanding*. Likewise, bivariate correlations indicated a moderate positive relationship between students' *awareness of RRI components* and *understanding of the controversial SSI*.

6. Discussion and conclusions

Science education is an important dimension of the European Commission's Responsible Research and Innovation (RRI) objectives; however, RRI is not an explicit focus of biology teaching and few biology teachers have experience in integrating RRI in classroom practice. The RRI and active citizenship module of the current study contributes to the connection of high school Biology education to empowering the next generation of citizens, scientists and researchers to be aware of their responsibility for the environment and the society in which they operate. The purpose of the present study was to investigate the effectiveness of an RRI and active citizenship biology module about cholesterol regulation using statins, in terms of students' conceptual understanding, understanding of the controversial SSI, awareness of RRI components, feeling of responsibility and willingness to act.

As part of this empirical exploration, two significant results were identified. First, the RRI and active citizenship module employed not only contributed to students' conceptual understanding and their understanding of the controversial SSI about cholesterol regulation with statins, but also to students' awareness of RRI components and students' active citizenship. Second, all five variables (conceptual understanding, understanding of the controversial SSI, awareness of RRI components, feeling of responsibility and willingness to act) emerged as interrelated factors. We next discuss these findings in more detail. The section will conclude with a set of relevant educational implications.

6.1. Effectiveness of the RRI and active citizenship module

This study documented the important increase in students' conceptual understanding regarding core concepts (e.g. cholesterol structure and function, cholesterol and fat absorption, heredity and enzymes, statins and their function, atherosclerotic plaque and cardiovascular system) as well as in students' understanding about the controversial SSI, due to their participation in the RRI and active citizenship module. Besides this increase, a significant improvement was recorded in students' awareness of RRI components as well as in students' feeling of responsibility and willingness to act.

Overall, while this RRI learning module provided increased *cognitive elements* (conceptual understanding, understanding of the SSI controversy and awareness of RRI components), active participation experiences in a controversial SSI contributed to promoting *socio-scientific accountability* (feelings of responsibility and willingness to act) as a key precursor to effective action. This can be attributed to the student-center, interactive and experiential activities designed especially for the RRI and active citizenship module. Previous studies (e.g., Roth, 2009; Lee et al., 2013) also reveal that feeling of responsibility and willingness to act can be developed by facilitating students to deal with engaging learning activities in the context of a controversial SSI.

6.2. Relationships between the investigated variables

The findings of this study shed light on the way the Conceptual Understanding (CU), Understanding of the controversial SSI (SSI), awareness of RRI components (RRI), Feeling of Responsibility (FR), and Willingness to Act (WA) are interweaved. As shown in Figure 3, CU is in the core of the five variables examined and plays a

crucial role for the other four variables. Moreover, it is evident that a knowledge triangle is formed that consists of *Cognitive Elements* with significant correlations between CU, SSI and RRI which consist of understanding three individual knowledge: Conceptual Understanding, SSI Controversy Understanding and the Awareness of RRI components. On the other hand, a *Socio-scientific Accountability* triangle is formed with significant correlations between CU, FR and WA with the FR and WA but with less pronounced correlations with CU.

These findings are opposed to previous studies supporting that content knowledge is not related to students' understanding of and decision-making about complex SSIs (e.g.Jho et al.,

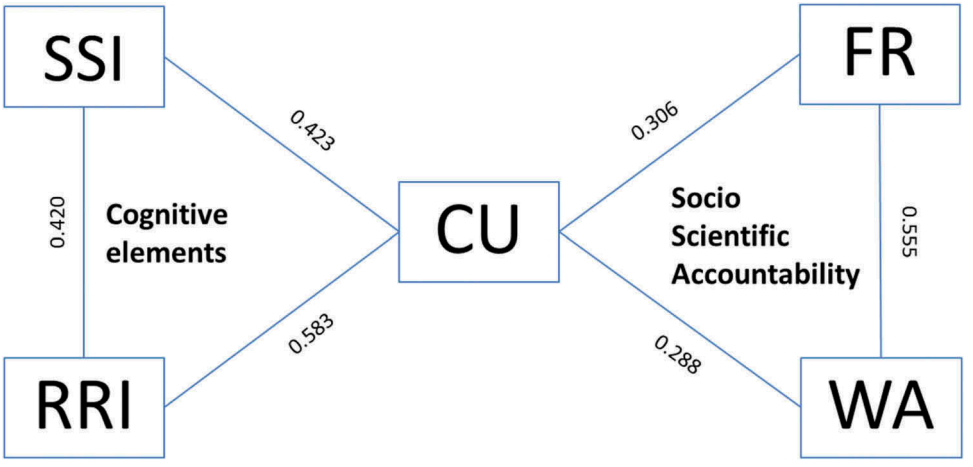

Figure 3. The main correlations between the variables measured. CU: Conceptual Understanding, SSI: SSI Controversy Understanding, RRI: Awareness of RRI components, FR: Feeling of Responsibility, WA: Willingness to Act.

2014). Instead, the present study provides empirical support to the argument that content knowledge not only plays significant role for the conceptualization of complex of SSIs (Kolstø et al., 2006; Sadler and Fowler, 2006), but it is also related with students' awareness of RRI components as well as with students' feeling of responsibility and willingness to act.

6.3. Educational implications

This research is timely since RRI in science education is quickly becoming an important policy topic while there is a lack of empirical studies in this field. It seems that there is a need for further research, particularly on the effects of learning interventions of RRI and active citizenship for preparing young students to become active and responsible future citizens. The promotion of learning activities that integrate RRI in the teaching strategies, appears as an important preparation for the education based on scientific knowledge (Gorghiu, Anghel, and Ion, 2015).

The findings of the present study also have several educational implications. First, it seems that the development of RRI and active citizenship modules can promote multiple learning gains such as content knowledge, understanding of the controversial SSI and awareness of RRI components, feeling of responsibility and willingness to act, without excluding that there may be other important types of learning gains we have not evaluated in this work. This is important not only for biology teachers but also for curriculum designers, teacher educators and instructional designers. Second, even though all of these five learning gains variables are interrelated it seems that students' conceptual understanding has crucial role for the other four variables. In turn, this reinforces the need for introducing RRI and active citizenship teaching in the content-based biology curriculum, where students' conceptual understanding could further facilitate the development of students' socio-scientific accountability as well as the promotion of other cognitive elements (e.g. understanding of a controversial SSI, awareness of RRI components).

Furthermore, given that the module employed in this study was designed by in-service biology teachers, it seems that educators can play an important role in making science more relevant to cutting edge controversial SSIs, when they are provided with well-crafted pedagogical frameworks, such as the Socio-Scientific Inquiry-Based Learning (SSIBL) framework and when they have the opportunity to participate in an effective professional development program. This might in turn increase the likelihood that students can apply what they have learned outside school and respond to societal challenges. Therefore, biology teachers should

have the opportunity to understand what RRI and active citizenship concept consists of and how the key aspects of this concept can be introduced in Biology lessons. Student-centered, interactive and experiential activities designed especially for the RRI and active citizenship module which was employed in the context of this study, enabled students' conceptual understanding, awareness of RRI components, understanding of the controversial SSI, while also promoted their socio-scientific accountability.

Biology education provides several themes where controversial SSIs could be examined by students based on the SSIBL framework. The nature of biological phenomena that greatly affect human life suggest that there is a great potential to incorporate the SSIBL pedagogical framework in everyday biology teaching and learning. In addition to the use of statins to regulating cholesterol levels in human body, other examples of controversial SSIs include a variety of health, ecology and environmental controversial SSIs such as genetically modified foods, the climate change, the electronic cigarette, the biological effects of nanotechnology, management of endangered species, the transplantation of human organs, organ donation and trading in human organs, antibiotics and vaccines. Biology classes could empower biology students for RRI and active citizenship. This could be another open window of the future of biology education.

Acknowledgments

Many thanks to all students and teachers who participated in this research.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was partially supported by the PARRISE, 7th FP, SiS-2013-2.2.1-1, [612438].

ORCID

Andreas Ch. Hadjichambis http://orcid.org/0000-0001-6833-7046
Yiannis Georgiou http://orcid.org/0000-0002-2850-8848
Eleni A. Kyza http://orcid.org/0000-0003-0992-4034

References

Association, A. H. 2008. Heart Disease and Stroke Statistics–2008 Update. Accessed: http://professional.heart.org/idc/groups/ahamah-public/@wcm/@sop/@smd/documents/downloadable/ucm_498848.pdf

Blumenfeld, P., B. J. Fishman, J. Krajcik, R. W. Marx, and E. Soloway. 2000. "Creating Usable Innovations in Systemic Reform: Scaling up Technology-Embedded Project-Based Science in Urban Schools." *Educational Psychologist* 35 (3): 149–164. doi:10.1207/S15326985EP3503_2.

Boyes, E., K. Skamp, and M. Stanistreet. 2009. "Australian Secondary Students' Views about Global Warming: Beliefs about Actions, and Willingness to Act." *Research in Science Education* 39: 661–680. doi:10.1007/s11165-008-9098-5.

Brugts, J. J., T. Yetgin, S. E. Hoeks, A. M. Gotto, J. Shepherd, R. G. J. Westendorp, A. J. M. de Craen, et al. 2009. "The Benefits of Statins in People without Established Cardiovascular Disease but with Cardiovascular Risk Factors: Meta-Analysis of Randomised Controlled Trials." *BMJ* 338: 2376.

Christenson, N., S. H. Chang Rundgren, and H. O. Höglund. 2011. "Using the SEE-SEP Model to Analyze Upper Secondary Students' Use of Supporting Reasons in Arguing Socioscientific Issues." *Journal of Science Education and Technology* 21: 342–352. doi:10.1007/s10956-011-9328-x.

Cross, R. T., and R. F. Price. 1999. "The Social Responsibility of Science and the Public Understanding of Science." *International Journal of Science Education* 21 (7): 775–785. doi:10.1080/095006999290435.

de Vocht, M., A. Laherto, and I. Parchmann. 2017. "Exploring Teachers' Concerns about Bringing Responsible Research and Innovation to European Science Classrooms." *Journal of Science Teacher Education* 28 (4): 326–346. doi:10.1080/1046560X.2017.1343602.

Eilks, I., and T. Feieraband. 2010. "Raising Student Perception of the Relevance of Science Promoting Communication and Evaluation Capabilities Using Authentic and Controversial Socio-Scientific Issues in the Frame Work of Climate Change." *International Science Education* 21: 176–196.

European Commission, 2017. Responsible Research and Innovation. Accessed: https://ec.europa.eu/research/swafs/pdf/pub_rri/KI0214595ENC.pdf

Golomb, B. A., and M. A. Evans. 2008. "Statin Adverse Effects: A Review of the Literature and Evidence for A Mitochondrial Mechanism." *American Journal of Cardiovascular Drugs* 8 (6): 373–418. doi:10.2165/0129784-200808060-00004.

Gorghiu, G., G. A. Anghel, and R. Ion. 2015. "Students' Perception Related to Sciences." *Procedia Social and Behavioral Sciences* 180: 600–605. doi:10.1016/j.sbspro.2015.02.166.

Heras, M., and I. Ruiz-Mallén. 2017. "Responsible Research and Innovation Indicators for Science Education Assessment: How to Measure the Impact?" *International Journal of Science Education* 39 (18): 2482–2507. doi:10.1080/09500693.2017.1392643.

Jho, H., H.-G. Yoon, and M. Kim. 2014. "The Relationship of Science Knowledge, Attitude and Decision Making on Socio-Scientific Issues: The Case Study of Students' Debates on a Nuclear Power Plant in Korea." *Science and Education* 23 (5): 1131–1151. doi:10.1007/s11191-013-9652-z.

Kaiser, F., S. Wolfing, and U. Fuhrer. 1999. "Environmental Attitudes and Ecological Behaviour." *Journal of Environmental Psychology* 19: 1–19. doi:10.1006/jevp.1998.0107.

Klosterman, M. L., and T. D. Sadler. 2010. "Multi-Level Assessment of Scientific Content Knowledge Gains Associated with Socioscientific Issues-Based Instruction." *International Journal of Science Education* 32: 1017–1043. doi:10.1080/09500690902894512.

Kolstø, S. D., B. Bungum, E. Arnesen, A. Isnes, T. Kristensen, K. Mathiassen, I. Mestad, A. Quale, A. S.Vedvik Tonning, M. Ulvik. 2006. "Science Students' Critical Examination of Scientific Information Related to Socioscientific Issues." Science Education 90 (4): 632–655. doi:10.1002/sce.20133.

Lee, H., J. Yoo, K. Choi, S. W. Kim, J. Krajcik, B. C. Herman, and D. L. Zeidler. 2013. "Socioscientific Issues as a Vehicle for Promoting Character and Values for Global Citizens." *International Journal of Science Education* 35 (12): 2079–2113. doi:10.1080/09500693.2012.749546.

Levinson, R. and PARRISE consortium. 2017b. Socio-Scientific Inquiry-Based Learning: Connecting Formal and Informal Science Education with Society. Accessed: http://www.parrise.eu/

Roth, W. M. 2009. "Activism or Science/Technology Education as Byproduct of Capacity Building." *Journal for Activism in Science & Technology Education* 1 (1): 16–31. Accessed http://www.wepaste.org/jaste1.1.html

Sadler, T. D., and S. R. Fowler. 2006. "A Threshold Model of Content Knowledge Transfer for Socioscientific Argumentation." *Science Education* 90: 986–1004. doi:10.1002/(ISSN)1098-237X.

Strippoli, G. F., S. D. Navaneethan, D. W. Johnson, V. Perkovic, F. Pellegrini, A. Nicolucci, and J. C. Craig. 2008. "Effects of Statins in Patients with Chronic Kidney Disease: Meta-Analysis and Meta-Regression of Randomised Controlled Trials." *BMJ* 336: 645–651. doi:10.1136/bmj.39472.580984.AE.

Zeidler, D. L., and B. H. Nichols. 2009. "Socioscientific Issues: Theory and Practice." *Journal of Elementary Science Education* 21 (2): 49–58. doi:10.1007/BF03173684.