Research in Science Education (2022) 52:1643–1658
https://doi.org/10.1007/s11165-021-10014-w

Exploring Undergraduates' Breadth of Socio-scientific Reasoning Through Domains of Knowledge

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Accepted: 21 June 2021 / Published online: 9 August 2021

Abstract

Socio-scientific issues (SSI) are informed by science concepts but require consideration of societal aspects in order to be effectively understood and resolved. As a result, functional scientific literacy necessitates fluency with science as well as other domains of knowledge when engaged in reasoning about science and societal dimensions of SSI (i.e., socio-scientific reasoning (SSR)). However, a holistic examination of those domains of knowledge that inform a particular SSI has not been undertaken. In this investigation, thematic analysis is employed to explore domains of knowledge undergraduates (N = 91) used when reasoning about a regionally relevant SSI after completing a semester-long course about contemporary water-related issues. We found that participants used a number of knowledge domains, including science and ethics, as well as domains from the social sciences, though the number and type of knowledge domains differed within and across SSR dimensions. These findings inform SSI research and instruction in the context of SSI, as they begin to make concrete the diversity of knowledge domains with which individuals need familiarity and which must be synthesized to effectively understand and respond to SSI and thus exhibit functional scientific literacy.

Keywords Socio-scientific issues · Socio-scientific reasoning · Domains of knowledge · breadth and depth analysis · Functional scientific literacy

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Introduction

Socio-scientific issues (SSI) are grounded in science but cannot be effectively resolved without addressing relevant societal dimensions (e.g., ethics, economics, morality). For most SSI, multiple courses of action exist, but none is likely to benefit all stakeholders equally. As a result, understanding and responding to SSI require individuals to understand and practice science concomitantly with drawing on their own moral compasses as they grapple with issues (Zeidler 2014). For this reason, SSI instruction is considered a gateway to the development of functional scientific literacy (Roberts and Bybee 2014; Zeidler & Sadler 2011).

SSI have long been considered meaningful and effective contexts for science instruction, as numerous investigations of SSI-based teaching have evidenced increases in content knowledge (Sadler et al. 2016; Venville and Dawson 2010), science practices (Zangori et al. 2017 ; Peel et al. 2019), and nature of science understandings (Khishfe and Lederman 2006). SSI instruction can also promote development of character and a propensity for engaging actively in citizenship (Lee et al. 2013)—competencies that draw from knowledge domains that are not scientific in nature. Only more recently, however, has the focus been put on practices associated with understanding and responding to SSI, or *socio-scientific reasoning* (SSR), which learners employ when understanding the issue's complexity, taking the perspective of stakeholders affected by the issue, inquiring about additional information necessary for understanding the issue, and engaging those information sources with skepticism. Although one might expect individuals engaging in SSR to incorporate a number of domains of knowledge that include science, ethics, economics, morality, etc., it has yet to be ascertained empirically how individuals draw on various domains of knowledge when attempting to understand and resolve SSI.

Domains of knowledge are specific concepts and activities associated with content domains, such as science, linguistics, or culinary arts (Aristotle 2009). Significant research has been conducted around the importance of domain-specific knowledge as opposed to knowledge that is domain general (Stevens et al. 2005), particularly in science (e.g., Zimmerman 2000). In this case, science is distinct from other knowledge domains because of how its knowledge is developed—through systematic collection and analysis of data, as well as its focus on natural phenomena (Kampourakis 2016). Science includes domain-specific knowledge, such as knowledge of atomic structure or natural selection, but also knowledge spanning other domains, such as ideas for constructing a compelling narrative or clear explanation, which would be considered more domain general. Although there is significant literature regarding knowledge for scientific reasoning, the breadth of knowledge domains that individuals draw on as they engage in SSR are not well understood.

Rationale for Study

Functional scientific literacy requires consideration of science and other non-scientific domains of knowledge (Roberts and Bybee 2014). Although scientific knowledge ranging from domain general to domain-specific has informed scientific literacy, less clear are the domains of non-science knowledge and how those domains inform reasoning about SSI. If functional scientific literacy requires fluency with knowledge domains that are not scientific in nature, then understanding what those knowledge domains are and how they are employed is requisite to aiding students in its development. In this study, we introduce a novel analysis of the Quantitative Assessment of Socio-Scientific Reasoning (QuASSR; Romine et al. 2017) to account for the breadth of SSR as a complement to the depth of SSR analysis that has traditionally been used to understand SSR. We argue that a dual *breadth and depth analysis* better accounts for the knowledge domains necessary for informed consideration and resolution of SSI. Our research was guided by following question: *How do learners draw on different knowledge domains as they engage in the different aspects of SSR?*

Functional Scientific Literacy

We find Robert and Bybee's (2014) heuristic for two visions of scientific literacy helpful. Vision I focuses on understanding and developing science knowledge in various ways to scientific ends and with the advancement of the scientific enterprise in mind. Vision II also accesses the concepts and practices of science, but with a focus on position-taking and decision-making that includes a variety of knowledge domains which, together with science knowledge, inform understanding of and response to societal issues. SSI are informed by science as well as other ways of knowing that are not scientific in nature, and privileging scientific reasoning while neglecting societal dimensions will ultimately lead to failed attempts at resolution (Levinson 2006). Thus, a strong argument can be made that Vision II scientific literacy is more functional than Vision I and that SSI serve as meaningful contexts for its development (Roberts and Bybee 2014).

Socio-scientific Reasoning

Sadler et al. (2007) introduced SSR as a means for exploring what students gained from engaging in socio-scientific inquiry, including the different dimensions of reasoning requisite to the informed consideration of SSI and those domains of knowledge such reasoning entails. They sought to identify practices related to character and informed citizenship that students developed alongside content knowledge through engagement in SSI. The SSR construct included four practices, or dimensions of reasoning, related to understanding and responding to SSI. These practices included recognizing the inherent *complexity* of SSI, examining issues from *multiple perspectives*, appreciating that SSI are subject to ongoing *inquiry*, and exhibiting *skepticism* when presented with potentially biased information (Sadler et al. 2007, p. 374). But what knowledge domains might students be expected to employ when engaging in the different dimensions of SSR? A look into the origins of knowledge domains and the evolution of their specificity provides some insight.

Domains of Knowledge

Understanding the origins of knowledge domains requires reaching at least as far back as antiquity. Greek culture held that "every art and every inquiry, and similarly every action and pursuit, aim[ed] at some good" (Aristotle 2009, p. 3)—the ultimate good being happiness and flourishing through virtue, especially in the face of adversity (similar to a functional vision for scientific literacy today). With this end goal in mind, Aristotle grouped knowledge into three domains: *theoretical* knowledge, such as physics and mathematics; *productive* knowledge, including creativity, planning, and execution (Grundy 1987) associated with such fields as engineering, agriculture, and rhetoric; and *practical* knowledge, which referred to the practical wisdom associated with character and citizenship, such as ethics and politics, and included *praxis*—informed action toward resolving contemporary issues (Grundy 1987)—not unlike those we consider as SSI today. Aristotle's three domains eventually migrated to Rome and became the *artes liberales*—seven disciplines necessary for civil society: the *trivium* (grammar, rhetoric, and logic) and *quadrivium* (geometry, arithmetic, music, and astronomy). Aristotle's simple classification of knowledge was ultimately expanded in terms of its disciplinary specificity to become "the main organizing principle for the division of labor in academic institutions, and … still plays a central role in structuring and organizing knowledge" (Hammarfelt 2019). Such disciplinary specificity has been criticized for stymying communication, innovation, and integration of knowledge necessary for resolving society's problems (Jacobs 2013). On the other hand, even if the multiplicity of academic disciplines could be reduced to a handful of domains, it would risk failing to capture the diverse methods and reasoning modes found within single disciplines (Brigandt 2010). A review of literature directed at understanding knowledge that has informed SSR should elucidate those domains that contribute to functional scientific literacy.

Domains of Knowledge Informing SSR

Sophisticated SSR includes the ability to employ various domains of knowledge that inform each dimension of SSR (i.e., *breadth of SSR*) as well as the ability to elaborate on or justify the importance of those domains of knowledge employed (i.e., depth of SSR). Studies of SSR have often employed the Quantitative Assessment of Socio-Scientific Reasoning (QuASSR; Romine et al. 2017), an instrument that measures SSR competencies. The QuASSR provides a focal SSI scenario, which is accompanied by open-ended items that correspond to the dimensions of SSR—the responses to which are analyzed using a rubric to score respondents' depth of SSR based on their ability to justify the importance of those domains of knowledge. Research using the QuASSR has been conducted with participants, including high school students and teachers. Across studies, participants' reasoning was found to rely on science knowledge, aspects of the nature of science, and economics, when engaging in SSR (Sadler et al. 2011; Kinslow et al. 2018). QuASSR research has documented student application of knowledge related to human health, economics, politics, and government (Kinslow 2018). Studies have also shown a wide range of sophistication regarding the different dimensions of SSR (Owens et al. 2019).

Studies of SSR have also been conducted that did not employ the QuASSR, and these, too, unearthed knowledge domains that informed reasoning. These studies employed various methods, including observations and interviews, discourse analysis, and multiple case study; and participants ranged from elementary students to undergraduates. Across these non-QuASSR studies, participants' SSR was found to rely on knowledge of economics, global politics, and ecology regarding issue complexity (Barab et al. 2007). SSR has also been shown to be informed by empathy (Simonneaux and Simonneaux 2009) and an ethic of care (Karahan and Roehrig 2017).

The literature reviewed highlights two important facets of SSR—reasoning sources to which participants refer when engaging in SSR (i.e., domains of knowledge) and justification of the use of those knowledge domains when considering the complexity, ongoing inquiry, perspective taking, and skepticism necessary for effectively understanding and responding to SSI. Across this literature, a number of knowledge domains informing respondents' SSR were identified and their abilities to justify them elucidated. However, none of the methodologies employed was conceived to capture a holistic perspective of the knowledge domains employed through engagement in SSR in the context of a particular SSI. One factor that may have limited the potential for gaining a better picture of the domains of knowledge used in SSR has been the analyses through which responses to SSR items have traditionally been understood. From its conception (Sadler et al. 2007), SSR has generally been evaluated using a four-point ordinal rubric to account for varying levels of SSR sophistication, where responses are scored for students' abilities to identify and justify up to two domains of knowledge for each dimension of SSR. Importantly, existing means for measuring SSR have well-accounted for students' depth of reasoning, but have not taken into account the various domains of knowledge that students employed, or the frequency with which those domains of knowledge appeared. This suggests that alternative, yet complementary, means other than the rubric for analyzing open-ended items to elucidate dimensions of SSR could be informative in terms of highlighting the domains of knowledge on which students rely for SSR.

Methods

In this study, we employed thematic analysis to better understand the knowledge domains that inform undergraduates' SSR about a regionally relevant SSI.

Study Context

This study was conducted in an introductory, interdisciplinary undergraduate course open to STEM and non-STEM students at a large Midwestern University. The course (Forbes et al. 2018) was designed to provide opportunities to build knowledge about natural and human dimensions of Earth's water systems and complex, real-world, water-related issues. One of the course goals was to support understanding of hydrological content knowledge, recognizing water's importance, and using that knowledge to reason about water-related challenges. Ninety-one of 98 undergraduate students enrolled in one of two offerings of the 3-credit course participated in the study (Table 1). Throughout the course, students considered concepts in hydrology as well as consideration of and discourse about water policy, history, and water management, in the context of contemporary water-related issues. The course was designed around a number of core tenets, including the use of best practices in STEM teaching and learning, scientific modeling, use of authentic datasets, and an emphasis on SSR and science-informed decision-making.

Instrumentation

SSR was elicited through use of the QuASSR. For this study, a new QuASSR scenario, the Raccoon River Nitrates Issue (RRNI), was developed as a means of challenging students to engage in reasoning about a complex water-related issue (Online Resource 1). The RRNI scenario consisted of a one-page description of the issue, followed by 4 forced-choice and

Table 1 Student demographic data by semester.

Year	Gender		Class				Major	
	Female	Male	Freshman	Sophomore	Junior	Senior/+	STEM	Non-STEM
1	16	22	10	11	9	8	30	15
2	30	23	2	28	15	8	37	9
Total	46	45	12	39	24	16	67	24

open-ended items (i.e., participants first respond to a yes/no prompt, then to an open-ended follow-up question based on their first response). Each question corresponded to one of the four dimensions of SSR. The RRNI scenario centered on a real-world dispute regarding agriculture and nitrate-laden drinking water. Specifically, nitrate runoff from farms was entering rivers that supply drinking water for downstream residents. The consumption of nitrate-laden drinking water reduces the capacity for blood to effectively move oxygen throughout the body, and the residents of a downstream community were fed up with having to fund the removal of nitrates from their drinking water. The decades old Clean Water Act that has long relieved farmers of responsibility for cleaning up the water they pollute, and the dependence of downstream citizens on the produce being grown on those farms, contributes to the complexity of the issue. Although participants were not introduced to the SSR construct as part of the course, they were taught about SSI and engaged with similar water-related SSI throughout the course (e.g., water well contamination, regional water balance), which included opportunities for reasoning through the different SSR dimensions. Thus, the expectation was that participants would be well-equipped to draw on a number of knowledge domains in their reasoning about this contemporary SSI.

Data Collection

Students completed the RRNI QuASSR during a 1-h block within a class session at the end of the course. They used laptops to complete the instrument through an online assessment platform. The data were cleaned and anonymized prior to analysis. It is important to note that, although researchers deemed the QuASSR to be the most appropriate source of data for answering the research question and sufficient for doing so, the study was limited by its reliance on the QuASSR as a single data source (Lincoln and Guba 1985).

Data Analysis

Data were analyzed in two phases. First, emergent open coding by way of a thematic analysis was employed to account for the *breadth of SSR* students exhibited for each dimension of SSR. The purpose of the thematic coding was to identify the breadth of sources that contributed to or served as the basis for participants' reasoning for each dimension of SSR. The researchers realized that the themes that had emerged in the first round of coding naturally clustered into domains of knowledge on which the participants drew when engaging in SSR. At that point, researchers overlaid an analytic framework based on knowledge domains to tease apart domains of knowledge represented across the themes that had emerged.

As a part of the thematic analysis, two researchers independently coded 20 participants' responses for each of the four SSR dimensions, noting any source of reasoning for each dimension. Then, the two researchers compared notes and source codes for each of the responses and reached consensus regarding the source codes to be assigned. This resulted in an emerging codebook of sources of reasoning for each dimension of SSR that included representative excerpts from student responses. Researchers then analyzed an additional 10 participants' responses using the consensus source codes to codify those as themes that were emerging in order to approach saturation. Finally, the two researchers used the emerging source codebook to independently code the remaining 61 participants' responses before coming together and reaching a consensus as to any codes that may have differed. Thus, themes resulted from the sources of reasoning identified in participants' responses regarding each dimension of SSR, and a frequency count was made for the number of responses in which each theme appeared. The researchers then identified excerpts from participants' responses to serve as exemplars (particularly vivid yet unnecessarily complex examples that most clearly represented each theme that emerged, Braun and Clarke 2006). These exemplars, as well as the themes and frequency counts to which they correspond, are provided in Tables 2, 3, 4, and 5. All excerpts are accompanied by a pseudonym to provide an indication of the diversity of participants' responses represented in the results.

In a second phase of coding that was *a priori* in nature, themes were clustered into their respective domains of knowledge for each dimension of SSR (definitions of the knowledge domains can be found in Table 6). Domains of knowledge included natural science (hereafter "science") and ethics, as well as social sciences, such as economics, politics, psychology, and sociology. Frequency counts were made for the number of responses in which each domain of knowledge was referenced for each dimension of SSR. The frequency of themes appearing in participants' responses regarding each dimension of SSR, as well as exemplars for each, are organized by domains of knowledge and provided as tables for each dimension and serve as the collective breadth of SSR exhibited by the participants about the RRNI.

Results

Participants engaged in SSR made use of knowledge from a number of domains, including economics, ethics, politics, psychology, science, and sociology, though participants used knowledge from more domains when reasoning about some dimensions of SSR than others (Figure 1). The findings that follow have been organized by SSR dimension.

Complexity

Participants engaged in reasoning about the complexity dimension of SSR by considering whether the RRNI could be solved easily. Participants' complexity-related reasoning employed all six of the domains of knowledge that appeared across SSR dimensions (n = 6, Table 2). Knowledge domains, such as economics, ethics, politics, and sociology, were regularly referenced during complexity-related SSR. Other domains, such as psychology and science, appeared much less frequently. The number of knowledge domains participants made use of in their responses ranged from 0 to 6, and on average, complexity-related responses drew on two knowledge domains (M = 2.03, $S.E.$ = 0.11).

Perspective Taking

Participants engaged in the perspective-taking dimension of SSR by considering how the major stakeholders, the farmers and the downstream residents, would respond to a proposed resolution that stated the best approach to solving the RRNI would be through voluntary conservation measures. Participants' use of knowledge domains ranged from 1 to 5 (M = 2.34, $S.E.$ = 0.08) and included economics, politics, ethics, sociology, and science knowledge (n = 5, Table 3). Interestingly, participants generally leaned heavily on some knowledge domains when engaged in perspective taking, such as sociology, politics, economics, and ethics, whereas only a few participants drew on other knowledge domains, such as science, in their perspective taking. In all cases in which participants employed science, it was done so in

Table 2 Domains of knowledge employed during engagement in complexity-related SSR.

Freq	Knowledge domain	Exemplar
64%	Sociology	
44%	• Human diversity	"The raccoon issue cannot be solved easily as it comprises many sectors having different ways of seeing the issue, so coming to the same conclusion will take a long time." (Gary)
26%	• Human cooperation	"It [would] be a challenge to get all parties to agree on a solution to the issue and to get all parties to comply with the decision." (Jenny)
12%	• Human well-being	"We can't tell people to suck it up and 'rub some dirt on it if they are suffering severe health issues due to the polluted water." (Katie)
55%	Economics	"If one was to say that farmers need to stop this fertilizer runoff then that would cost the farmers a lot of money . . . The other option is for the city to adopt a nitrate filtration system, but that . . . would not be economically feasible." (Jack)
33%	Politics	"The state would also have to put in some regulations stating what is a safe amount of fertilizer that can be allowed to runoff a farm and then they would have to enforce these regulations with every farmer in these counties." (Sally)
30%	Ethics	"This problem draws in ethical and moral questions as well as who is legally in the right, which is never an easy problem to solve." (Joan)
15%	Science	
13%	• Limits of human understanding	"It would be hard to see how much fertilizer and nitrates are running off of each individual farm." (Sally)
8%	• Scientism	"The RRNI should be easy to solve because there are many different options that are available with today's technology." (Dave)
8%	Psychology	"This is a difficult problem to solve because people with different values don't see eye to eye with one another." (Pete)

Note: Where multiple themes clustered within a knowledge domain, those are indented and bulleted

Table 3 Domains of knowledge employed during engagement in perspective-related SSR.

Freq	Knowledge domain	Exemplar
78%	Sociology	
76%	• Progress	"[Des Moines residents] may respond positively as this is a step towards clean water in the river." (Chris)
5%	• Public opinion	"This might actually be the best case scenario for Big Corn as it shows cooperation but little effort." (Said)
70%	Politics	"The farmers do not want someone marching onto their land telling them how to fertilize their crops." (Stu)
50%	Economics	"[The farmers] want to be able to grow a good crop and that loss of nitrates is a loss of input cost going down the drain and they will want to lower their input cost." (Jonathan)
32%	Ethics	
15%	• Stereotyping	"[The farmers] would not voluntarily do something like this because it is adding more work for them. Also, if the pollution does not affect them, they probably do not care enough. (Stephanie)
12%	• Justice	"[Des Moines residents] would feel as if they are being cheated - they are subjected to unclean water and severe diseases while the farmers get off essentially free from consequence." (Van)
11%	• Responsibility	"[Des Moines residents] would believe that the farmers are at fault." (Lori)
5%	Science	"The farmers seem to be the easy ones to blame, but in all reality it could be any given source. There can be toxic levels of nitrate runoff in prairies too, it is merely the way the soil works to promote healthy plant life. In a region of the Mid-west where the soil is very fertile naturally, the nitrate levels are higher in a normal point and time." (Cory)

Note: Where multiple themes clustered within a knowledge domain, those are indented and bulleted

Table 4 Domains of knowledge employed during engagement in inquiry-related SSR.

Freq	Knowledge domain	Exemplar
75%	Science	
63%	• Problem	"It is the fertilizers being used that are causing the rise in nitrates levels?" (Brad)
41%	• Solution	"What alternatives are there to fertilizing with nitrates?" (Ned)
35%	Economics	"Whether or not the city can afford to continue removing the nitrates from the water." (Sally)
13%	Sociology	
9%	• Human diversity	"What can be done to bring the urban and rural community together?" (Stu)
4%	• Human cooperation	"How the residents using the river water are willing to cooperate to solve the problem." (Lila)
2%	• Human well-being	"I would like to see more statistics [on] the number of people directly impacted by the water, disease rates, [and] death rates over the years." (Katie)
8%	Politics	"What are the water policy and laws of the area regarding groundwater and surface water?" (Jack)

Note: Where multiple themes clustered within a knowledge domain, those are indented and bulleted

taking the farmers' perspective, such as by arguing that adopting conservation-appropriate farming practices would be in their best interest (e.g., improve their soil) or that the variable nitrate levels of naturally fertile Midwestern soils were the cause of the nitrate-laden water. No participants used science to bolster the position of the downstream residents.

Table 5 Domains of knowledge employed during engagement in skepticism-related SSR.

Freq	Knowledge domain	Exemplar
80%	Ethics	
53%	• Funding bias (FB)	"When an organization funds a research most of times the results come in their favor since they are paying the scientist." (Blair)
26%	• FB—misrepresentation of finding	"They would find the same levels but not publicize that it is the same." (Carrie)
19%	• FB—biased methodology/non--representative sampling	"The farmer-appointed scientists may attempt to take their measurements at times or places where the nitrate levels are lower in order to show that they are not doing as much damage as the city says they are." (Georgia)
14%	• FB—purposeful employment	"The farmers would hire scientists that would find the results that benefit farmers." (Natalie)
22%	• Science is unbiased	"The scientists, no matter who they're hired by, are held to a standard of integrity that goes beyond the conditions of their employment." (Vinsk)
38%	Science	
37%	• Similar nitrate levels	"The nitrate level [would] be constant [because] scientific procedures are standard [so] the result should be also standard [and] we should not expect a deviation." (Ed)
1%	• Different nitrate levels	"With a constantly shifting water system it is possible that scientists could find different nitrate levels based on a variety of factors in the same sampling areas. The depth of the water, time of day, temperature of the water, biological activity, etc. could all impact the nitrate levels in the river. I believe that even a non-biased group of scientists could find slightly different results." (Joe)

Note: Where multiple themes clustered within a knowledge domain, those are indented and bulleted

Table 6 Definitions of knowledge domains that participants employed during SSR engagement.

Knowledge domain	Definition
Economics	Knowledge of the production, distribution, and consumption of goods and services
Ethics	Knowledge of what is morally right and wrong
Politics	Knowledge of law-making organizations regarding governance
Psychology	Knowledge of the human mind and its influence on behavior
Science	Knowledge and a system of developing knowledge about the natural world
Sociology	Knowledge of society, including the relationships between humans living in groups social institutions

Note: All definitions above were paraphrased from dictionary.cambridge.org

Inquiry

Participants engaged in inquiry-related SSR regarding the kinds of additional information they would need to make a decision about how to resolve the RRNI. Participants' use of knowledge domains ranged from 0 to 3 (M = 1.34, $S.E.$ = 0.08) and included science, sociology, economics, and politics (n = 4, Table 4). Importantly, whereas the vast majority of participants pointed to gaps in science knowledge when indicating additional information they would need to resolve the RRNI, nearly half of participants suggested only needing scientific knowledge, and a tenth indicated needing no additional information at all. That no participants requested additional ethical knowledge as part of their inquiry-related reasoning is notable, given the important role that morals and ethics play in understanding and responding to SSI.

Skepticism

Participants engaged in the skepticism dimension of SSR by considering whether scientists hired by the farmers and scientists hired by the downstream residents would find the same

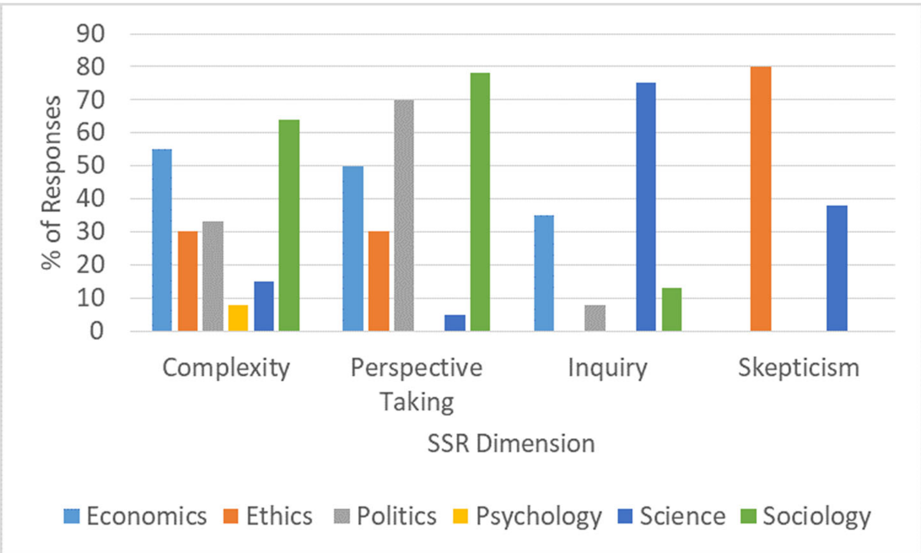

Fig. 1 Domains of knowledge that informed each dimension of SSR

level of nitrates when measuring water samples around the Raccoon River. Participants' use of knowledge domains ranged from 1 to 2 ($M = 1.19$, $S.E. = 0.01$). Notably, ethics and science were the only domains of knowledge on which participants drew while engaging in skepticism-related SSR ($n = 2$, Table 5). While 22% of participants reasoned using both types of knowledge, 59% used only ethical knowledge and 17% used only scientific.

Discussion

With this study, we sought to better understand the domains of knowledge that inform functional scientific literacy by looking at learners' use of knowledge from various domains as they engage in SSR. We found that undergraduates draw on a number of knowledge domains while engaging in SSR, including science and a number of others that range from ethics, economics, and politics to sociology and psychology. Whereas researchers have previously argued that the integration of science, technology, engineering, and mathematics (STEM) is likely requisite to understanding and effectively responding (Zeidler 2016; Owens & Sadler 2020), these findings indicate that the synthesis of information from a number of additional domains is also necessary. Additionally, these findings substantiate some the earliest Western ideas regarding liberal arts and the knowledge requisite for participation in democratic societies (Grundy 1987; Jacobs 2013), reinforcing that a theoretical understanding of science alone is insufficient for resolving the world's most pressing issues (Aristotle 2009) In the paragraphs that follow, we discuss differences in domain knowledge use within and across dimensions of SSR and the entangled nature of the domains of knowledge pertaining to participants' SSR and then conclude with implications for researchers and educators.

Variation in Domains of Knowledge Usage Across SSR Dimensions and SSI Contexts

Although the participants engaging in SSR drew on a number of knowledge domains, more knowledge domains were employed during reasoning in some dimensions than others. For example, only a few individuals indicated that the diverse beliefs of those involved in the RRNI contributed to its complexity, but other SSI, such as genetic modification or climate change, where beliefs might be more integral to the issue, might warrant a greater use of psychology-related knowledge (Sadler and Zeidler 2004; Sinatra et al. 2014). Similarly, participants drew on science knowledge less frequently during complexity-related SSR than other dimensions, such as inquiry or skepticism. It may be the case that nitrate-laden agricultural runoff associated with the RRNI can be attributed to irresponsible farming practices that lead to negative environmental and health consequences, and as such, the pertinent science knowledge is both well-understood and accepted. In this case, science information would still be necessary for understanding and responding to the SSI (i.e., inquiry) and need to be considered critically (i.e., skepticism), it just would not contribute to the complexity of issue.

Although science knowledge may not contribute to the RRNI's complexity, it likely does in other SSI contexts. For example, experimental gene therapy is likely to be informed by science that is not as settled and thus contributes to that issue's complexity. This suggests that the use of domains of knowledge not only varies by SSR dimension within the context of a single issue; it may also vary by SSI context. For example, in this study, participants drew on ethical knowledge when engaged in all dimensions of SSR except for inquiry-related reasoning.

Given that the RRNI is taking place in these participants' backyard (the Midwest), it may be that they see the experiences and perceptions that inform their ethical stances as similar to those involved in the RRNI, and thus, this particular SSI does not necessarily warrant additional consideration of the diverse ethical perceptions that often accompany cultural differences across stakeholders regarding an issue. Other SSI might require additional inquiry into the ethical domain. For example, there is a current move toward drilling for oil in Alaska, with likely repercussions on one of the few remaining salmon runs on which local indigenous populations have traditionally relied. Given the importance of salmon runs to indigenous culture in Alaska, differences between indigenous and western worldviews, and that the code of ethics that evolved among the indigenous cultures did so separately from those of the western world, it is possible that SSR about an SSI such as this one might warrant requests for information about ethical norms outside of those espoused by Midwesterners engaging in SSR. Interestingly, among the 91 undergraduates who served as participants in this study, many were from countries outside the USA that ranged from developing to developed and potentially included individuals whose cultures and ethical norms significantly differed from those espoused in contemporary America.

It is important to note that the manner in which the qualitative analysis was conducted may have constrained the number of knowledge domains that appeared in a given dimension of SSR. For example, participants' engagement in skepticism-related SSR was confined to two knowledge domains: ethics and science. In many ways, this could be expected, as skepticism refers to a healthy doubt of the validity of a claim, science is a claim-making, fundamental truth-seeking process, and ethics govern any move away from truthful to more biased accounts. However, our finding that skepticism was relegated to ethical and scientific knowledge domains may be somewhat misleading. For example, in this study, participants who indicated that they expected the scientists to be biased suggested that the bias would benefit the source of funding (e.g., the scientists hired by the farmers would be expected to find results that pleased the farmers who hired them). In this case, though mention of bias is a breach of ethics and therefore correctly identified as ethical knowledge, participants indicated that the bias was likely motivated by economic interests. However, it is equally plausible to think that bias could be motivated by any number of conflicts of interest that span knowledge domains. For example, a scientist looking to grow clout in her or his research field might adopt methodologies that yield significant results, in which case the motivation for bias would fall into the sociological domain. Similarly, individuals whose beliefs do not allow for them to accept the legalization of abortion might seek to emphasize findings that support life starting at conception, in which case the motivation for bias would fall into the psychological domain. As such, bias is ethical in nature and motivated by a "conflict of interest," wherein the individual engaged in the ethics breach (in this case, the scientist) biases findings in a way that aligns with their interests, whether they be economically, politically, sociologically, or psychologically motivated. In this way, skepticism could be linked to a number of knowledge domains, rather than only ethics and science.

Science and Societal Knowledge Domains Not Easily Disentangled

We found that participants drew on the scientific knowledge domain to some degree when reasoning across all SSR dimensions, providing further evidence that the social contexts in which SSI reside cannot be cleaved from the science that informs them (Zeidler 2014). Interestingly, cleaving the socially-oriented knowledge domains from one another appears to be a difficult task as well. We found knowledge domains, such as ethics, economics, and politics, to be intermingled in these undergraduates' reasoning and not easily disentangled. Although this finding is limited to a single SSI context, contemporary examples are abundant. For example, the previous presidential administration in the USA tampered with the language of science documents concerning climate change to reduce public perception of the impact of fossil fuels with the presumed intent of keeping their base of support pleased. SSR in this instance would certainly be informed by knowledge from the political domain. However, the base of support the administration was seeking to please has significant investment in the continued use of fossil fuels. In this case, the administration's tampering with climate change language in science documents has implications for both science and ethics; these are informed by politics and economics, such that none of these knowledge domains can be cleanly parsed as our coding suggests. It may be that Aristotle recognized the entangled nature of knowledge domains when he proposed his simple classification of knowledge into theoretical, productive, and practical, which happen to align nicely with resolving SSI (Grundy 1987). Alternatively, the disciplinary specificity that currently structures liberal arts and contemporary academia acknowledges the numerous disciplines that inform participation in a democratic society such that considering them on their own is worthy (Brigandt 2010; Jacobs 2013). However, no matter which end of the specificity spectrum educators might find themselves, it is important that educators recognize that students draw from a number of knowledge domains when making sense of SSI. This study identified a number of those domains which can serve as fertile starting points for strengthening their ability to reason about SSI.

Implications

This study has implications for the manner in which SSR is operationalized, measured, and described. The SSR construct and the QuASSR assessment have effectively provided a concrete means for researchers looking to measure learners' SSR and for instructors looking to enhance their students' reasoning skills. However, one factor that may have limited the potential for gaining a clearer picture of the domains of knowledge used in SSR has been the analyses through which SSR has traditionally been understood. From its conception (Sadler et al. 2007), SSR has generally been measured using rubrics that account for varying levels of SSR sophistication, where responses were scored for students' abilities to identify and justify more than one domain of knowledge for each dimension of SSR. Although this analysis has well-elucidated the depth of students' reasoning about SSI, it has not illuminated the breadth of knowledge domains that students employ when doing so. For example, although functional scientific literacy necessarily requires the evaluation of moral and ethical aspects of SSI (Zeidler et al. 2005; Zeidler and Sadler 2011), the traditional means for measuring perspective taking-related SSR has thus far failed to account for or appreciate moral/ethical aspects of SSI. Furthermore, the traditional analysis has not accounted for the frequency with which knowledge domains have been employed nor the means by which they were employed across dimensions of SSR. Given that functional scientific literacy requires fluency with a number of knowledge domains beyond science, researchers should seek alternative means, such as thematic analysis for analyzing open-ended items and elucidating dimensions of SSR. This would be informative in terms of highlighting the breadth of knowledge domains on which students rely for SSR and complement the rubrics to determine the depth with which they are considered, together accounting for the breadth and depth of SSR.

Additionally, these findings have implications for the manner in which SSR is promoted in classroom settings. Given that students draw on and elaborate/justify ideas from different domains of knowledge when engaging in SSR, it is important for educators to get a grasp of those knowledge domains their students are drawing on. In this study, we employed a thematic analysis to access such information and recommend this as a viable means for collating domains of knowledge during SSI instruction. Armed with a set of domains of knowledge, educators can direct focus toward elaborating on or justifying the contributions of each of those domains of knowledge toward better understanding and effectively resolving the issue. It is important to note that not every knowledge domain students initially draw on is effectively justified or warranted. For example, in this study, we found participants engaged in perspective taking to draw on and justify economics as to why farmers both would and would not support a proposed resolution. Instances such as these provide rich contexts for students to either recognize that they need more information or to disregard attempts to justify knowledge domains such as economics where it is not warranted. Such instruction would aid students in recognizing the breadth of knowledge domains pertinent to reasoning about given SSI, as well as being able to elaborate as to why those knowledge domains are important to understanding and resolving the issue. We feel that this would provide instructors with means to scaffold the development of SSR while highlighting the importance of each student's perspective toward sense-making about the issue.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11165-021-10014-w.

Acknowledgements We thank the Water for Food Global Institute and the students in the course.

Funding This work was supported by the National Science Foundation (DUE-1609598).

Declarations

Disclaimer Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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