INTEGRATION OF STATISTICAL REASONING, SCIENTIFIC REASONING AND NATURE OF SCIENCE UNDERSTANDING THROUGH CITIZEN SCIENCE[1]

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Sound decision-making necessitates an appreciation of the role of uncertainty in generating data-based scientific knowledge, which calls for coordinating between different types of reasoning with statistical, scientific, and nature of science uncertainties. This study examines the uncertainties that young students articulate as they engage in activities designed to concurrently foster all three types of reasoning, and also explores how these types can interrelate. The context of Citizen Science is particularly suited for this goal, providing a unique opportunity to engage learners in authentic scientific practices including data analysis. We offer the Deterministic Relativistic and Middle ground (DReaM) framework, which consists of nine sub-categories of uncertainty articulations. We utilize it to analyze a case study of middle school students' participation in an interdisciplinary learning sequence, as part of the Radon Citizen Science Project. Some of the identified uncertainty articulations sub-categories and their interrelations will be illustrated during the Satellite Conference presentation.

INTRODUCTION AND BRIEF SCIENTIFIC BACKGROUND

The COVID-19 pandemic has reified the already established importance of cultivating citizens' data-based decision-making skills in a world of uncertainty. These everyday decisions integrate at least three types of reasoning: statistical reasoning (e.g., what are the chances of getting infected if you are vaccinated?), scientific reasoning (e.g., how does the vaccine work?), and understanding of the nature of science (NOS; e.g., what is reliable scientific knowledge? What is trustworthy vaccine-related research?). Tasked with the mission of preparing the young learners of today to become responsible decision-making citizens of tomorrow, the goal of reform education should therefore be to foster and integrate all three types of reasoning. Concepts or activities that are central to all three types of reasoning have greater potential to promote this goal (Dvir & Ben-Zvi, 2022).

As part of the latter effort, this study focuses on students' articulation of one central shared concept – *uncertainty*. In the context of statistical reasoning, uncertainty stems from the need to connect data and chance, requiring negotiations between two seemingly contradictory notions: the sample's representativeness (of a larger population) and sampling variability (i.e., how different a sample may be from that larger population) (Manor et al., 2014). Mature uncertainty articulations that accompany this type of reasoning are probabilistic in nature, however novices tend to articulate one of two extreme views: (1) a *deterministic statistical uncertainty* view expressed through little or no uncertainty; or (2) a *relativistic statistical uncertainty view* expressed through full or extreme levels of uncertainty. Nurturing students' statistical reasoning necessitates supporting them to also develop the more mature, probabilistic, middle ground view (Makar et al., 2011).

Although stemming from different sources, uncertainty articulations are likewise central in the context of scientific reasoning. One main source of scientific uncertainty articulations is the core scientific practice of coordinating data and theory (Gasparatou, 2017). Mature scientific uncertainty articulations reflect the bidirectional relation between data and theory and account for the two seemingly contradictory roles data play in coordinating the two – confirming and refuting prior theories (Chalmers, 2013). Acknowledging only one of the two can manifest in what we refer to as either *deterministic scientific uncertainty articulations* (expressing little or no uncertainty when data is only perceived as potentially confirming) or *relativistic scientific uncertainty articulations* (expressing extreme uncertainty when data is only perceived as potentially refuting), and mature articulations necessitate expressing a middle ground integrating these two extreme views (Popper, 1963).

Uncertainty articulations are also central to reasoning with the NOS, particularly when reasoning with the tentative but valuable nature of scientific knowledge. Building on Hofer and Pintrich's (2001) framework, we suggest that, similarly to the other two types of reasoning, naïve views of the nature of scientific knowledge also take the form of one of two extremes: *deterministic NOS uncertainty articulations* (expressing little or no uncertainty when scientific knowledge is perceived as

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fixed), or *relativistic NOS uncertainty articulations* (expressing extreme uncertainty when knowledge is perceived as highly refutable).

Building on these parallel frameworks to depict novices' uncertainty articulations in relation to each of the three types of reasoning, we introduce the integrated *DReaM framework* (Deterministic Relativistic and Middle ground) (Table 1). By suggesting a shared language integrating what has so far been discussed separately for each type of reasoning, to describe and explore students' uncertainty articulations in relation to the three types of reasoning: two extreme (deterministic or relativistic) categories, and one mature category that serves as a middle ground, successfully negotiating and coordinating between the two extreme views. The integrated framework can allow us to build on previous disciplinary-specific accounts of students' emergent uncertainty articulations, most prevalent in statistics education literature, (e.g., Ben-Zvi et al., 2012), and extend them by exploring the less charted waters of how the three types of uncertainty articulations interrelate or can be concurrently nurtured. The latter, however, requires a setting that has the potential to support all three.

Table 1: The DReaM holistic framework categories to concurrently describe and analyze students' Statistical, Scientific and NOS (SSaN) uncertainty articulations.

	Relativistic (full uncertainty)	Middle ground	Deterministic (no uncertainty)
Statistical reasoning	Sampling variability	Sample's representativeness is evaluated alongside sampling variability	Sample's representativeness
Scientific reasoning	Data can completely disprove theory	Theory is derived from and challenged by data	Data can completely confirm theory
NOS reasoning	Knowledge is refutable	Knowledge is tentative and self-corrected but valuable	Knowledge is fixed

Authentic learning environments, which allow students to meaningfully experience scientific research, significantly contribute to improving students' NOS understanding (Edmondson at al., 2020), scientific reasoning and, if include engagement with authentic data, statistical reasoning. Therefore, engaging students in real-world ongoing science projects, such as Citizen Science projects, can concurrently foster the three types of reasoning, and elicit and nurture the three types of uncertainty articulations associated with them.

Citizen Science

Citizen Science is transforming the way scientific knowledge is created, in that citizens participate in authentic scientific research (Bonney et al., 2015). The public's involvement in science produces a body of reliable data and information, which is available for the use of scientists, decision-makers, or the public itself (McKinley et al., 2017). The ways that the public participates in these project are diverse, but often the main role is limited to assisting in the data-collection phase. The public's role could be expanded to include participation in other research aspects, such as the data analysis phase (Golumbic et al., 2020).

Including students as part of the participants in Citizen Science projects, especially if this participation goes beyond mere data gathering, provides an opportunity to combine the learning of scientific contents with first-hand experience of scientific research practices (Schuttler et al., 2019). This experience can foster habits of scientific reasoning along with a deeper understanding of the various scientific methods to study, describe and explain the world (Phillips at al., 2018), as students are allowed to contribute to authentic, real-world scientific endeavors.

In this study, the students' engagement in the Citizen Science project was guided by the project's scientific goals and practices. We claim that such engagement has the potential to concurrently foster students' SSaN reasoning, as it can allow students to gain a broader understanding of the deep underlying shared or complementary principles of the three types of reasoning and the uncertainty that is at the core of each of them. Examining students' uncertainty articulations can illuminate what sources of uncertainty they acknowledge and the uncertainty-related considerations they develop through the integrated experience, allowing us to identify how to support students' capitalization of the potential advantages of integrating the three types of reasoning in the unique setting of Citizen Science.

METHOD

To this end, we offer a case study of one pair of middle school students' engagement in an extended learning sequence as part of a Citizen Science project. In this unique setting, we explore the different uncertainty articulations that the pair expressed, how these shifted throughout their participation and the roles that the interrelations between their SSaN uncertainty articulations played in these shifts. This article examines the question: *What SSaN uncertainty articulations can young students express, and how can the different types of uncertainty articulations interrelate in the context of integrating SSaN reasoning?*

The Radon Citizen Science Project

The participants of this research engaged in the TCSS[2] Radon gas Citizen Science project (Tsapalov et al., 2020). The goal of this project was to design a meaningful educational experience for learners, that attends to the Radon's scientists research needs (e.g., collect data about Radon Concentration Levels, RCLs). One innovative aspect of the designed experience was that it was inspired by the scientists' authentic goals and the practices they employ to promote them. For the purpose of this research, the students engaged in an extended learning sequence with the goal of helping the scientists not only by providing data but also by exploring it, and the various SSaN uncertainty considerations relevant to these data.

The setting and learning sequence

The learning sequence was inspired by the way the scientists conduct their research. The learning sequence included multiple experiences with exploratory data analysis, informal statistical inference (Makar et al., 2011), and statistical modeling (Dvir & Ben-Zvi, 2018). The goals of this sequence were aligned with those of the scientists, intended to promote students' engagement with scientific uncertainties. The learning sequence was also extended to include more explicit examinations of students' NOS understanding and the uncertainties that might relate to it. We focus on the first five activities of seven activities in the learning sequence (a total of 13 hours)[3]. Two researchers (the first two authors) accompanied the students' participation.

The participants

The findings we report here are taken from a pilot study that focused on one pair of students, in preparation for a wider (full classroom) implementation. The pilot study was conducted after school hours, in a classroom at the local university. The pair chosen for this case study were Liv and Yoni, both academically successful 13 (grade 8, Liv) and 14-year-olds (grade 9, Yoni) from a public middle school in northern Israel. The pair were chosen as they agreed to participate in the study, were communicative and open, thus were able and willing to share their thoughts, beliefs and uncertainties, and to explain their views and opinions. Both students had no prior experience with statistics or data investigations.

Data collection and Analysis

The pairs' actions and articulations during all the activities (seven 60 minute-sessions, including one individual semi-structured pre-intervention interview) were documented, to examine students' uncertainty articulations in relation to their emergent SSaN reasoning from several points of view and capture all aspects of the students' participation. The pair's investigations and discussions were fully videotaped using Camtasia™ or Zoom and a stationary camera to simultaneously capture their computer screen and their conversations and actions, accompanied by hand written documentation by one of the researchers. All of the students' artifacts (e.g., hand-written notes and worksheets) were collected. The data corpus of the first five activities this article focuses on, was carefully transcribed and annotated for further analysis of the students' articulations.

The analysis took a qualitative approach, corresponding to the objective of developing new theories that offer a holistic interpretation of complex phenomena. This approach views reality as a subjective entity that can be examined through several points of view (cognitive, socio-cultural, etc.). The research method applied is that of an instrumental case study of one pair of students' participation in the adapted learning sequence, serving as a means to obtain insights beyond the studied case itself (Stake, 1995), due to the exploratory nature of the pilot study, and the purpose of providing an in-depth account for a rich and complex phenomenon that has not yet been explored. The data were analyzed using an interpretative microgenetic method (Siegler 2006), considering the speakers' discourse, actions, gestures, and interactions. This method allows for a detailed observation of changes in students' articulations in relation to their reasoning.

To guarantee maximal "trustworthiness" (Creswell, 2012), inferences about students' articulations in relation to their reasoning were made only after finding sufficient evidence from all of the data sources and after considering alternative interpretations from different perspectives and theories. The data analysis was validated using a two-tiered triangulation method (Schoenfeld, 2007): the first triangulation tier requires agreement between the researchers, while the second triangulation tier requires consistency across resources and theories. Reliability was achieved through constant data comparisons amongst the research group members, comprehensive data use, and verification of the sources' accuracy in terms of form and context.

FINDINGS

In the Satellite Conference presentation, we shall introduce key scenes from the students' participation in the first five activities in the learning sequence (episodes A-F). We shall first present the students' initial uncertainty articulations during their individual pre-intervention interviews, episodes A and B (those unique to each student, followed by one type of articulations that was expressed by both), and the introductory activity, episode C. We then describe their uncertainty articulations in the subsequent engagement with investigating growing samples size 24, 48, and 72, episodes D, E and F, to illustrate how these shifted. Table 2 summarizes the DReaM uncertainty articulations categories that the students expressed throughout the learning sequence. The "Views" column is colored according to the students' articulated view: white for *relativistic* views, dark gray for *deterministic* views, and light gray for *middle ground* views.

Table 2: Yoni and Liv's SSaN uncertainty articulations.

Section	Activity's title and label	Views
[redacted]		
A)	Yoni's Initial interview	Yoni's pre-intervention relativistic scientific and NOSUn articulations
B)	Liv's Initial interview	Liv's pre-intervention deterministic NOSUn articulations
A&B)	Both initial interviews	Shared pre-intervention deterministic StatUncertainty articulations
C)	The introduction activity	Deterministic statistical and ScUncertainty articulations
[redacted]		
D)	1st data investigation (n=24)	Conflict between extreme uncertainty articulations, and the emergence of middle ground StatUncertainty articulations
E)	2nd data investigation (n=48)	Additional emergent middle ground articulations whilst still shifting between extremes
F)	3rd data investigation (n=72)	Reconciling conflicting extreme uncertainty articulations through middle grounds

DISCUSSION

While the students expressed a wide variety of uncertainty-related articulations, overall, using our *DReaM framework*, these can be classified as either (a) related to the NOS, specifically the tentative nature of scientific knowledge and experimental results; (b) related to scientific reasoning, specifically the relation between data and theory; and (c) related to statistical reasoning, specifically the ability to formulate statistical inferences.

While engaging in the various activities elicited different uncertainty articulations from each of the students, a shared pattern was observed in the shifts in their expressions. In this pattern, an extreme view of uncertainty was initially articulated. An opposite extreme view was articulated almost concurrently. Gradually, more and more mature middle ground uncertainties (Gasparatou, 2017) were articulated. The process of gradually resolving seemingly conflicting beliefs or understandings (e.g., in the context of statistical uncertainty, Manor et al., 2014), was evident in all three SSaN uncertainty categories. This process was likely fueled by the deep interconnections between these uncertainty categories, and the designed setting and learning sequence. While the DReaM framework accounted for the various types of uncertainty articulations that the students expressed, the shared pattern in the students' uncertainty articulations suggests it can be further extended.

CONCLUSIONS

Fostering students' reasoning with SSaN uncertainties, although essential in today's information age, has long been a challenge as many novices tend to intuitively articulate extreme uncertainty views (Ben-Zvi et al., 2012; Gasparatou, 2017; Popper, 1963). Concurrently cultivating and integrating all three types is even a greater challenge, but the innovative setting of Citizen Science offers new pedagogical opportunities as it allows for the concurrent engagement with authentic scientific and statistical practices (Schuttler et al., 2019). To explore these, we implemented an extended learning sequence to accompany young students' participation in the Radon Citizen Science project, designed to elicit and nurture all three types of uncertainty articulations. While our focus pair initially expressed extreme and naïve uncertainty articulations, both students gradually expressed the more mature and middle ground balanced view. Various design aspects seemed to facilitate these shifts: the data themselves, the adaptation of the data investigation to the unique nature of the Radon scientific context and the authentic scientists' goals in the citizen science project.

While these three aspects were central to the integrated introduction of the students to SSaN uncertainties, one potential limitation of such a design is that it can expose deeply rooted conflicts between students' initial views and beliefs (Dvir & Ben-Zvi, 2022). These should be expected, particularly as the cultures of science and statistics can endorse inconsistent values and purposes (e.g., valuing cause-and-effect explanations versus valuing descriptive explanations). Furthermore, as our findings indicate, such conflicts can ultimately be the greatest instigators for growth and progressions, creating the dual pull necessary for students to find more mature middle grounds. However, successfully harvesting the pedagogical potential of these conflicts necessitates the consideration of additional aspects of design, such as fostering productive discussion norms.

Despite its idiosyncrasy, this case study illustrates the affordances and utility of the DReaM theoretical framework's depiction of the interrelations between the nine uncertainty sub-categories. The framework builds on, and contributes to, ongoing discussions in each of the three fields of statistics, science and NOS education. Particularly, the DReaM framework extends insights drawn from research on uncertainty in the context of statistics (e.g., relativism vs. determinism), to the other two contexts, and informs all three fields about the power of integrating SSaN uncertainty and reasoning. Nevertheless, to extend its contribution, the initial framework should be further examined with additional students, different age groups and different Citizen Science projects. Additional aspects related to the three types of reasoning, besides uncertainty, should also be examined to further the theoretical discussion of how these reasonings interrelate, but also, illustrated here by the students' conflicts, of their inconsistencies. These are vital for future pedagogical insight that will allow us to better prepare the students of today for responsible citizenry tomorrow.

ENDNOTES

[1] This article is based on: Aridor, K., Dvir, M., Tsybulsky, D., & Ben-Zvi, D. (2023). Living the DReaM: The interrelations between statistical, scientific and nature of science uncertainty articulations through citizen science. Instructional Science. https://doi.org/10.1007/s11251-023-09626-8.
[2] TCSS – Taking Citizen Science to Schools Research Center (https://www.tcss.center/home-en).
[3] For more information about the Radon learning sequence please see: Connections 2020.

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