RE-DESIGNING TECHNOLOGY-ENHANCED LEARNING SEQUENCES TO CONCURRENTLY NURTURE YOUNG STUDENTS' STATISTICAL, SCIENTIFIC, AND NATURE OF SCIENCE REASONING

Michal Dvir and Dina Tsybulsky
University of Haifa and Technion Israel Institute of Technology
dvirmich@gmail.com

Current global events have reified the importance of cultivating citizens' data-based decision-making skills. The often-scientific nature of the context of these everyday decisions calls for integrating at least three types of reasoning: statistical, scientific, and the nature of science (NOS) reasoning. Fostering all three and their integration has become instrumental. Educational technologies can support this effort, facilitating technologically-enhanced activities to introduce novices to disciplinary cultures. We re-designed a technology-enhanced learning sequence extending the engagement of middle school students in authentic, ongoing scientific Citizen Science projects. Our case study illustrates three aspects of design that can be consequential in concurrently nurturing students' statistical, scientific, and NOS reasoning: authenticity to statistical and science practices; consideration of students' naïve views and challenges; and affordance of the technological tool.

INTRODUCTION

In today's information age, informed, data-based decisions often integrate at least three types of reasoning: statistical reasoning, scientific reasoning, and understanding of the Nature of Science (NOS). As part of an effort to explore productive means to foster and integrate all three, we report on an innovative interdisciplinary project, capitalizing on the unique pedagogical potential of incorporating students in Citizen-Science projects. The activity sequence designed for this project was an adaptation of a pedagogy originally designed to foster statistical reasoning, integrating authentic statistical and scientific practices in ways that are accessible to middle school students (ages 13–14). The latter was made possible by engaging students with TinkerPlots, a software designed to foster young students' statistical reasoning (Konold & Miller, 2015), that was repurposed to also nurture their scientific reasoning. The learning sequence included additional scaffolding to elicit the students' emergent and changing NOS perspectives. We provide a case study of one pair of students' participation in these activities and discuss consequential aspects of design.

BACKGROUND

This section introduces statistical, scientific, and NOS reasoning; the unique setting of Citizen Science; and the pedagogy that was adapted to concurrently nurture all three types of reasoning.

Statistical Reasoning

Statistical reasoning includes reasoning with key statistical ideas such as variation and uncertainty (Garfield & Ben-Zvi, 2008), as well as reasoning with endorsed means of engaging in statistical practices such as statistical data investigations, statistical inferences, and statistical modeling (e.g., Dvir & Ben-Zvi, 2021). Statistical reasoning also includes appreciation of the role of context as well as general (e.g., seeking explanations) and specifically statistical (e.g., recognition of the need for data) types of thinking and dispositions (Wild & Pfannkuch, 1999). Any of these may be non-intuitive for novices and for young learners in particular. One challenge may be the mathematics often formally used to engage with many of these notions, leading many to explore informal (i.e., with little or no mathematics) adaptations (Pfannkuch et al., 2018). These are in line with current views that favor learning through participation in technology-enhanced activities. Specifically, repeated experiences with exploratory data analysis supplemented with informal statistical inference and modeling activities (Dvir & Ben-Zvi, 2021) can support learners' statistical reasoning. Because the practices of data investigation and modeling are also central scientific practices, these statistical activities can likewise foster learners' scientific reasoning, particularly if the context of the investigation is scientific (Groth, 2018). However, despite being characteristic of both science and statistics, these practices have different implementations and disciplinary purposes. Benefitting from their dual pedagogical potential requires a better understanding of the interrelations between statistical and scientific reasoning.

In S. A. Peters, L. Zapata-Cardona, F. Bonafini, & A. Fan (Eds.), *Bridging the Gap: Empowering & Educating Today's Learners in Statistics. Proceedings of the 11th International Conference on Teaching Statistics (ICOTS11 2022), Rosario, Argentina.* International Association for Statistical Education. iase-web.org

Scientific Reasoning

As in statistics, reasoning with data plays a central role in scientific reasoning and is the focus of key scientific practices: experimentation, observation, and classification (Erduran & Dagher, 2014). However, whereas the goal of statistical data investigations is often generating data-based *general* claims, i.e., inferences (Makar et al., 2011), the goal of scientific research is referred to as coordinating new or pre-existing theories with new and previously generated data (Chalmers, 2013). The latter implies several distinctions between scientific and statistical data investigations. First, whereas in statistics it is rare to consider previously generated data to formulate inferences, the promotion of scientific knowledge calls for interpretating and reinterpreting many past experiments, to which new data is added. Similar to statistics, prior data-based theories inform pre-investigation hypotheses. However, the interpretation of new data-based results is not merely intended to support or refute hypotheses, but rather to promote a more encompassing theory that can explain the new, as well as prior results (Gasparatou, 2017). Having a different purpose, scientific investigations employ strategies that differ from (at least classical) statistics, such as induction or deduction, argumentation, and theorizing cause-and-effect mechanisms, all of which are necessary aspects of scientific reasoning. Despite these distinctions, scientific and statistical data investigations are based on several shared ideas related to various "styles of reasoning" such as experimental evaluation, hypothetical modeling, categorization and classification, and probability (Kind & Osborne, 2017). Cultivating the reasoning that supports both statistical and scientific activities necessitates not only the development of various strategies but also suitable values and norms and a mature understanding of the nature of science.

Nature of Science Reasoning

Whereas statistical and scientific reasoning refer to more disciplinary-specific aspects of each practice, the Nature of Science (NOS) refers to broader issues such as what science or scientific knowledge are, how science can be conducted, and the bi-directional relation between science and society (McComas & Clough, 2020). Cultivating more mature views of these NOS issues is considered an inseparable aspect of introducing novices to the culture of science and supporting their development of both scientific skills and critical dispositions (Hodson, 2014). Although essential to various aspects of responsible citizenry and everyday decisions, many have naïve perceptions about NOS-related notions (García-Carmona & Acevedo-Díaz, 2018). In particular, novices tend to (a) view scientific knowledge as static, well founded facts, which are not to be challenged or revised, as opposed to the tentative nature of scientific knowledge; (b) overvalue insight on "why things happen" as opposed to "what exists" (Kind & Osborne, 2017); and (c) consider the purpose of science to be solely generating explanatory theories, as opposed to also providing predictive classifications (Erduran & Dagher, 2014). To nurture more mature views, many have advocated for explicit reflective engagement with NOS ideas and immersing in authentic scientific contexts and settings (Edmondson et al., 2020). This advocates for supplementing scientific and statistical data investigation activities with explicit discussions about students' current and changing views of NOS understandings. If these are also conducted as part of real, ongoing scientific endeavors, such as Citizen Science, they can be even more beneficial, fostering concurrently students' scientific, statistical, and NOS reasoning.

Citizen Science

Citizen Science is a new research genre, capitalizing on the affordances of incorporating the public in ongoing authentic scientific research to extend the scientific knowledge that can be generated. Although the main role ascribed to the public is often limited to assisting in projects' data-collections, it can be expanded to include participation in other research aspects such as the data analysis phase. The latter provides an opportunity to learn about the scientific contents of the project as well as to experience authentic scientific research practices (Schuttler et al., 2019). If students are the participating public, engaging in activities of scientific, project-generated data investigations has the potential to concurrently foster students' statistical, scientific, and NOS reasoning. However, the project-generated data are often large in scale, collected by untrained individuals, and are constantly being expanded (Kjelvik & Schultheis, 2019). Young students can find these complexities too challenging. Furthermore, the scientific purpose of the data collected can be an additional aspect of contextual complexities and might not be appropriate for novices and young students. Designing activities of exploring these data to concurrently nurture the three types of reasoning necessities addressing students' potential challenges whilst still being authentic to aspects of the scientific interest in the data and the authentic scientific and statistical practices of exploring them. To meet this pedagogical challenge, this research repurposed a technologically-enhanced pedagogy originally designed to foster novices' statistical reasoning, to support students' scientific and NOS reasoning through engaging in Citizen-Science-generated data investigations.

Repurposing the Integrated Modeling Technologically-Enhanced Approach

The Integrated Modeling Approach (IMA; Manor & Ben-Zvi, 2017) was originally designed to support young learners' statistical reasoning and was inspired by three extensively explored statistics education pedagogies: Exploratory data analysis (EDA; Tukey, 1977), Informal Statistical Inference (ISI; Makar & Rubin, 2018) and probability modeling (e.g., Pfannkuch et al., 2018). The IMA suggests a unique form of integrating the three. The IMA learning sequence begins with students conducting a real-world data investigation, in which the students use TinkerPlots to intuitively create various data representations and explore them. The goal of their data exploration is to formulate ISIs about a population larger than their sampled data. This goal encourages students to experience and articulate uncertainty-related concerns. To explore these concerns, students then engage in follow-up, probability modeling activities: designing a dynamic model using the TinkerPlots Sampler, generating multiple random simulated samples from the model, and comparing between them (Manor & Ben-Zvi, 2017). The latter provides a potent experience of the sampling process and of related abstract statistical ideas at the heart of statistical reasoning (Dvir & Ben-Zvi, 2021).

Technology is key in facilitating the IMA learning sequence. It affords the construction of various visual representations without using mathematics (Cobb, 2007), and the TinkerPlots Sampler affords a tangible experience of statistical abstract notions such as random variability. Technological tools have also been found to be beneficial in supporting students' scientific reasoning (e.g., Falloon, 2019) but are particularly beneficial when their use is supplemented by additional forms of instruction (Hillmayr et al., 2020). This implies that computer-enhanced data activities such as those suggested by the IMA can concurrently support students' statistical and scientific reasoning, but the overall activity must be carefully designed. To extend the pedagogical potential of IMA to nurture students' scientific and NOS reasoning, in this study we explored a repurposed IMA-inspired learning sequence designed for a particularly scientifically challenging Citizen Science project. The main design considerations were engaging students with relevant, authentic statistical and scientific practices, students' potential naïve views and challenges, and the affordances of TinkerPlots. In the context of the repurposed learning sequence, we focused on one pair of middle school students' participation, to examine: *What articulations of statistical, scientific, and NOS reasoning can middle school student express? How can these transform throughout the learning sequence, and what aspects of design were consequential in these transformations?*

METHOD

This study was conducted as part of a collaboration between Connections, a longitudinal design and research project (begun in 2005), and a biology education research group collaborating with the Taking Citizen Science to School (TCSS) research center. We employed an instrumental case study approach (Stake, 1995) to provide in-depth accounts of the statistical, scientific, and NOS reasoning one pair of middle school students articulated, and how their reasoning changed as they participated in the project's preliminary research in the context of the Radon Citizen Science project.

The Radon Citizen Science Project

The pair participated in the repurposed IMA-inspired learning sequence that included eight 90-minute-lessons as part of the Radon TCSS project. The learning sequence began with an introductory activity, and in accordance with the IMA, was followed by real-world and subsequent probabilistic data investigations. The design of these investigations was inspired by one of the projects' authentic scientific purposes: modeling a currently unexplained behavior that is unique to radon, namely the radon temporal variation (frequent, substantial, non-systematic fluctuations). An additional inspiration for the repurposed design was the measuring tool developed by the project's scientists that students were to utilize to collect data. The measurement given by this tool is relatively complex, the mean Radon Concentration Level (RCL) over four days. Students were to ultimately examine the big data set collected by all project participants. To support engagement with the latter data, the students began by examining data from an additional authentic data set collected by the scientists in their lab, originally for the purpose of ensuring the lab adheres to health regulations. The students gradually examined 24 (one day), then 48 (two days), and finally 72 (three days) hourly radon measurements taken from the additional data set. The students' goal during their real-world data investigations was to "learn more about radon," meaning (a) to experience and model its temporal variation and (b) to emergently consider the mean as representative. They utilized the TinkerPlots software to explore and compare these data. In a follow-up probability modeling activity, they utilized the TinkerPlots Sampler tool for an adapted IMA purpose of students' examining sampling variability to (a) discover that a four-day measurement (the authentic duration of the scientists' measurement tool) is significantly more representative than three and (b) develop an estimation of the maximum error of a four-day mean.

Participants, Data Collection, and Analysis

The focus pair, Liv and Yoav, were middle school students from a public school in northern Israel. Both were open and articulate and thus were able to share their thoughts and considerations. Neither had prior experience with data investigations. All sessions were videotaped by Zoom, concurrently documenting the students' computer screen, actions, and articulations. Videos of the pair's participation were transcribed and analyzed according to the interpretative microgenetic method (Siegler, 2006), to identify any statistical, scientific, or NOS considerations they implied. These were later categorized to identify repeated, thematically related considerations and how these had transformed throughout the pairs' investigation. Any shifts, however nuanced, were further explored to identify what design aspect, if any, played a role in their appearance. Key scenes were triangulated.

RESULTS

This section focuses on one prevalent theme of articulations that emerged from our analysis: *data-based claims*. This theme is central to both statistics and science and thus allows us to provide a rich but organized illustration of key aspects of students' initial and transforming statistical, scientific, and NOS reasoning. Overall, we identified four versions of this type of articulation. Version 1 was explanatory cause-and-effect claims, such as "because the window was open, the RCLs were low." These articulations reflected relatively naïve scientific and NOS reasoning (e.g., cause-and-effect can fully explain phenomena, and explaining why things happen is the only valued scientific knowledge). Version 2 was descriptive data depictions, such as "443 was the mean of the quantities *that day*." These articulations reflected relatively naïve statistical and NOS reasoning (e.g., data cannot provide general insight and data-based knowledge is fully tentative). The students initially articulated the first two versions during the pre-intervention interviews but also throughout the learning sequence. During the first data investigation, the two versions converged into version 3, descriptive data depictions that would apply to identical, and later similar, environmental conditions such as "in the same conditions as this [day] it [RCLs] will look the same." These articulations reflected more mature statistical, scientific, and NOS reasoning (e.g., initial acknowledgements of statistical uncertainty, scientific categorization and classification, and more balanced NOS views). However, the students' reluctance to formulate any generalized prediction still reflected somewhat naïve statistical (e.g., full as opposed to more balanced uncertainty) and NOS views (e.g., knowledge is fully tentative). Specially, the higher value they attributed to cause-and-effect explanations seemed to inhibit their willingness to offer any potentially generalizable prediction (e.g., "I don't understand how we can make an inference about an entire year… A lot can happen in another day that would affect my data") and resulted in their more frequently articulating version 1 claims.

Only after recognizing aspects in the data that remained stable as the students explored the second sample, were they willing to articulate more generalized data-based predictions, version 4, such as "usually in the noon and evening there will be less [RCLs] than in other hours." These articulations can be considered ISIs and thus reflect more mature statistical reasoning as well as scientific and NOS reasoning (e.g., cause-and-effect can explain *some* of the variation; probabilistic reasoning can produce valued but tentative scientific insight). Despite articulating version 4, the students still expressed concerns regarding the validity of their inferences due to potentially changing environmental conditions (version 1), and constantly oscillated between all four versions. However, as the third sample still reflects the same stable aspects they acknowledged earlier, Liv began to more frequently express version 4. Yoav, despite exhibiting the ability to articulate ISIs, remained reluctant, because he seemed to only value *why things happen* types of scientific explorations (e.g., “we look at this [data] without the why … not thinking, not opening our minds”). It was only during the subsequent probability modeling task that Yoav became more willing to articulate version 4, as yet again, the students noticed stable behaviors of the data. In this case, they noticed similarities between simulated samples. The latter reflected Yoav had gradually come to appreciate more the NOS value of *knowing what exists*, expressing more mature NOS as well as statistical and scientific reasoning (e.g., using probability for predicative classifications).

All three main design aspects were consequential in supporting this process. One design aspect that supported the emergence of version 3 was the *authenticity of the data activities to statistical practice* and the radon projects' *scientific goals* that illustrated the NOS value of discovering what exists and the utility of predicative classifications (not just developing explanatory theories). Consideration of *previously established naïve statistical and scientific views* was another consequential aspect of design that facilitated the students’ gradual and more frequent articulation of version 4. Specially, the variation they experienced with each larger sample and how it differed from the previous sample(s) challenged their initial cause-and-effect articulations and raised their uncertainty. However, the students’ gradual noticing of aspects of the data that remained stable as they explored larger (and later simulated) samples, provided them with more confidence to formulate more generalizable, however tentative, data-based claims. *Utilizing the unique affordances of the technological tool* was likewise consequential for allowing students to effortlessly explore and transition between various data representations, supporting their oscillation between cause-and-effect and descriptive claims (version 1 and 2) and their integration into version 3. The TinkerPlots Sampler was instrumental in focusing the students on non-systematic sources of uncertainty, as opposed to their initial focus on cause-and-effect (reflected in their frequent expression of version 1). The latter facilitated the students’ further exploring the potential and limitations of forming more generalizable, descriptive version 4 claims, reflecting more mature NOS, statistical and scientific reasoning.

CONCLUSIONS

Our goal is to illustrate what aspects of designing a technologically-enhanced learning sequence can be consequential in concurrently fostering middle school students’ statistical, scientific and NOS reasoning. This research contributes to ongoing discussions, typically centred on the role that the three design aspects we identified can play in promoting one of the three types of reasoning. Authenticity to practice, for example, has long been advocated but explored either in the context of nurturing students’ statistical (e.g., Dvir & Ben-Zvi, 2021) or scientific reasoning (e.g., Hodson, 2014). Students’ naïve NOS views as they engage in authentic science practices have likewise been explored (e.g., McComas & Clough, 2020), but little has been examined about how they can be fostered through engagement in authentic statistical inquiries. Although far from being exhaustive, this research seeks to promote the under-explored potential of concurrently fostering these three types of reasoning through one, cohesive, learning sequence, in the unique setting afforded by Citizen Science.

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