Promoting students' informal inferential reasoning through arts-integrated data literacy education

Structured abstract

Purpose

Arts-integration is a promising approach to building students' abilities to create and critique arguments with data, also known as informal inferential reasoning (IIR). However, differences in disciplinary practices and routines, as well as school organization and culture, can pose barriers to subject integration. We describe synergies and tensions between data science and the arts, and how these can create or constrain opportunities for learners to engage in IIR.

Design/methodology/approach

We co-designed and implemented four arts-integrated data literacy units with 10 teachers of arts and mathematics in middle school classrooms from four different schools in the United States. Our data include student-generated artwork and their written rationales, and interviews with teachers and students. Through maximum variation sampling, we identified examples from our data to illustrate disciplinary synergies and tensions that appeared to support different IIR processes among students.

Findings

Aspects of artistic representation, including embodiment, narrative, and visual image; and aspects of the culture of arts, including an emphasis on personal experience, the acknowledgement of subjectivity, and considerations for the audience's perspective, created synergies and tensions that both offered and hindered opportunities for IIR (i.e., going beyond data, using data as evidence, and expressing uncertainty).

Originality/value

This study answers calls for humanistic approaches to data literacy education. It contributes an interdisciplinary perspective on data literacy that complements other context-oriented perspectives on data science. This study also offers recommendations for how designers and educators can capitalize on synergies and mitigate tensions between domains to promote successful IIR in arts-integrated data literacy education.

Keywords

Arts-integration, data literacy, data science education, middle school, classrooms, co-design, informal inferential reasoning, interdisciplinary learning, STEAM

Introduction

Youth live in a society abundant with data, in which data-based arguments frequently support journalism and advocacy, but are also accompanied by risks of misinformation (Tandoc and Kim, 2022). Increased access to, and use of private and public data have led to a shift in mathematics education from emphasizing developing students' understanding of core statistical concepts and skills related to measures of central tendency and percentages, toward developing students' informal inferential reasoning (IIR) about data (Franklin & Bargagliotti, 2020). IIR is defined as "the way in which students use their informal statistical knowledge to make arguments to support inferences about unknown populations based on observed samples" (Zieffler et al., 2008, p. 44). This reasoning includes making sense of data and data patterns in terms of their real-world context and implications, raising questions about the data-based inferences and uncertainty, using data as evidence for claims and predictions, and making generalizations that extend to broader contexts and populations (Ben-Zvi et al, 2015; Franklin & Bargagliotti, 2020; Pfannkuch, 2007; Makar & Rubin, 2018; 2009).

Informal inferential reasoning can provide middle grades students with a critical foundation for engaging data literacy. While formal statistical inferential reasoning requires an understanding of complex statistical concepts that middle school students do not typically have, informal inferential reasoning can provide an entrypoint and pathway toward formal statistical reasoning for students with a range of formal statistical mathematics backgrounds (e.g., D'Ignazio and Klein, 2020; O'Neil, 2016; Pangrazio and Sefton-Green, 2022; Perez, 2019; Wild and Pfannkuch, 1999). Moreover, IIR's focus on generalizing to real-world contexts can invite students to reason about their personal and community connections to data and the implications of these data for themselves and society.

Data reasoning—whether formal or informal—is interdisciplinary: it requires one to draw upon knowledge and practices from multiple disciplines to create meaning from context (Briggs, 2002, 2023; Madison, 2002; Radke et al., Rubin, 2005, 2022; Scheaffer, 2001). For example, in interpreting and predicting numerical patterns of species decline across various continents, learners need to draw upon knowledge and skills from mathematics, biology, social studies, and environmental science, to make data-based claims that require an understanding of the human and environmental factors and for the mathematics and statistical approaches to gathering and modeling patterns in the data. Middle grades students face challenges in drawing on the knowledge across multiple disciplines required for IIR Typical school-based approaches to teaching about data tend to take place in mathematics classes that foreground mathematical processes often lack opportunities for learners to appreciate the sociopolitical and cultural contexts of data necessary to fully reason about the implications of the statistical patterns that they identify (Bhargava *et al.*, 2015; Philip *et al.*, 2013; Rubin, 2021; Wolff *et al.*, 2016).

The case for data-art inquiry

Integrating data science with arts has the potential to foster students' IIR, as these disciplines share practices of exploring, sensemaking, critiquing, and communicating about issues (Table 1). These disciplinary intersections create possibilities to engage students who might not otherwise engage in mathematics, and to reinforce learning across these shared practices. While the arts consist of a broad spectrum of creative activities, we define arts as a set of practices that involve the creation of an artifact—written, visualized, sonified, or performed—for the purpose of self-expression. Especially in contemporary art, artistic expression tends to be valued by how it situates personal experiences within broader societal issues, thus offering social commentary, and evoking emotional reactions of audiences by both connecting to an audience's experiences, and revealing otherwise untold perspectives (Bevan *et al.*, 2019). Thus, data-art inquiry is an arts-based approach to inquiry that involves using artistic practices and forms to represent patterns in data—and in some cases, to generate data—with the goal of evoking audiences' emotional responses to issues (e.g., Jordan, 2009; Miebach *et al.*, 2022).

Data-art inquiry can build IIR practices and disciplinary knowledge, and broaden engagement in data literacy. Ir draws on arts-based inquiry approaches that center critical and reflective practices (Blumenfeld-Jones, 2016; Halverson, 2021), that and offer opportunities to humanize data science education (D'Ignazio and Klein, 2020; Lee *et al.*, 2021) by encouraging an awareness of the subjectivity inherent in data generation and communication, and of the personal and societal consequences of that subjectivity (D'Ignazio, 2017; Friel *et al.*, 2001; Lee *et al.,* 2022; Pfannkuch *et al.*, 2004; Sorto, 2006). The creative aspects of artistic expression in arts-based inquiry can generate new and innovative approaches to visualizing, interpreting and sharing data-based claims (Aslan et al., 2014). Arts-integrated data literacy education can also broaden inclusion of learners by providing alternative, personally relevant , and equally valid ways of engaging with data (Bhargava *et al.*, 2015; Conner *et al.*, 2017; Radke *et al.*, 2023; Stone, 2022). With both data and art recognized as tools for advocacy and social impact, data-art inquiry can support more learners to participate in social discourses (Fam *et al.*, 2018; Henriksen, 2018; Meijias *et al.*, 2021; Shapiro, 2022).

Table 1. Alignments in inquiry practices between data science, the arts, and data-art inquiry, adapted from Bevan *et al.* (2019)

	Data Inquiry Practices	**Arts Inquiry Practices**	**Data-Art Inquiry Practices**
Goal	To inform through conveying objective information on an issue.	To evoke an emotional response from an audience.	To communicate data in a way that evokes action with data.
Explore	Identify a question. Determine what data, and how to collect it to answer that question.	Identify an issue of artistic worth by reflecting on one's personal experiences in relation to global ones.	Identify a problem or question using data to reflect on one's personal experiences in relation to global ones.
Make meaning	Use statistical and other analytic processes to answer the question.	Expand one's perspective on the issue through immersion, observation, and experiences.	Use formal and informal inferential reasoning, combined with subjective experiences, to answer the question

			or describe a perspective in relation to a broader pattern or trend.
Critique and communicate	Interpret data and infer implications for people impacted. Use conventions for building objective arguments from evidence.	Use aesthetic strategies to create an artifact that expresses a message. Step away to determine how it resonates with personal feelings and understandings of the issue.	Convey a perspective or argument on an issue based on data. Use aesthetic strategies to evoke an emotional reaction from audiences.

Data-art inquiry for informal inferential reasoning

The arts can support the three interrelated processes of IIR (Makar and Rubin, 2007): (1) *Going beyond the data* to make generalizations about a population (e.g., predictions, parameter estimates, claims) (Ben-Zvi, Gil and Apel, 2007; Curcio, 1987; Rossman, 2008); (2) *Using data as evidence* for those generalizations; and (3) *Expressing uncertainty* about those generalizations. Arts-based data literacy approaches present opportunities for *going beyond the data* by encouraging learners to contextualize data by making connections between data and their personal or local ecologies. Learners' personal knowledge of a data set's history or the situation it references can shape engagement with that data (Lee *et al.*, 2021), and sometimes, personal knowledge is required because the data are about their families, their communities, or even their own bodies (e.g., Kahn, 2020; Lee and Dubovi, 2020; Van Wart *et al.*, 2020). Arts-integrated data literacy approaches also broaden opportunities for *using data as evidence* to substantiate generalizations, as it widens the landscape of what may be considered useful, valid evidence (including qualitative, not just quantitative evidence), as well as the ways in which evidence can be represented and aesthetic goals such representations may have (i.e., evoking a certain emotion). These opportunities can offer alternative entry points to understanding and working with data that may help engage more learners. Finally, arts integration offers unique opportunities for *expressing uncertainty* about generalization, as they can surface the inherent subjectivity in the collection, interpretation, and use of data in argumentation.

Disciplinary cultures

Disciplinary practices arise from unique disciplinary cultures. When creating discipline-integrated learning experiences, it is crucial to acknowledge the intersections of these cultures. By *culture,* we refer to the personally- institutionally- and domain-shaped values, reflected in a domain's accepted methodologies for generating knowledge, and in the practices and routines for teaching within a domain (Warren et al., 2020). Culture also shapes the forms and ways of using *representations*, that is, the domain-specific standards and expectations for what counts as, and how to represent knowledge, evidence, and argument.

The culture of data science values both technical skills needed to make valid data-based claims from large data sets as well as visualization and storytelling practices that can engage non-experts with data findings (Wolff et al., 2016; Yau, 2013). Typical data visualizations map measurable variables onto graphic elements (e.g., line, space, color, shape) to highlight quantitative patterns and trends across a population. In contrast, the culture of arts education values reflection on personal or shared lived experiences, observation of qualities and patterns of one's chosen subject, and expression of multiple perspectives (Winner *et al.*, 2020; Halverson and Sawyer, 2022). The varied media and approaches to creating artworks encourage new approaches to the expression of abstract ideas, emotions, memories, and stories, which are not as expressible in numbers. Arts-based practices such as *close looking, self-reflection, critique,* and *exhibition*, can also cultivate IIR practices by encouraging learners to attend to details that might otherwise not be seen, and to make mindful choices about how to express ideas. Through such practices, students can come to re-see familiar ideas from new perspectives; to reason about the roles of context and perspective in shaping the meaning and implications of data; to explore questions about, and uncertainties in data; to consider how aesthetic strategies can evoke particular audience reactions to data claims; and, by presenting their work to external audiences, to see how data and the arts can allow them to contribute their perspectives to broader societal discourses. Thus, the integration of data science and the arts offers opportunities to mutually strengthen practices of analysis and communication in both domains, challenging learners to use data to generalize their personal experiences, while also representing the social and environmental context and implications of their data-based claims. However, tensions can also emerge as students attempt to create data-art that satisfies the values of each discipline.

Cross-domain synergies and tensions

In spite of its benefits, there are also many hurdles to integrating arts and data literacy in formal learning environments, including challenges of teacher preparation, and of the availability of time and resources necessary to support cross-domain co-design and instruction (Campbell *et al.*, 2021). In response to these challenges, arts-integration falls along a spectrum, where on one end, the arts is used in service of mathematics and statistical learning goals (e.g., design a poster to communicate survey findings); and on the other, the arts and data literacy are fully integrated such that values and practices of each are mutually supportive of the other's learning goals (Mejias *et al.*, 2021). At this latter end of the spectrum, students may learn values and practices not just *within* a discipline, but *through* a discipline, and ultimately transfer these to other contexts and domains (cf. Halverson and Sawyer, 2022).

Extending our previous work on data-art inquiry learning (Authors, DATE), this current study considers how the cultures of arts and data science, including their values and representations, intersect to produce the disciplinary synergies and tensions that either create or constrain opportunities for students' IIR. Figure 1 illustrates how we conceptualize arts and data science practices and representations to be uniquely shaped by the disciplinary cultures in which they are embedded; and how we propose synergies and tensions to emerge from the intersection of these cultures. This conceptualization builds on Meijias et al.'s (2021) notion of arts-integrated STEM—in which we include data science—as mutually instrumental and pedagogical. More specifically, our view of data-art inquiry is one in which the learning goals of each of data science and the arts have equal weight; and moreover, contribute to advancing learning both within and across their disciplinary boundaries. At the same time, we recognize that such disciplinary alignments are not always feasible in practice. Thus, we refer to *synergies* as the realization of epistemic alignments between data science and the arts (e.g., exploration, sensemaking, critiquing) (cf. Bevan *et al.*, 2019; Blumenfeld-Jones, 2016; Tygel and Kirsch, 2016), such that they are mutually supportive of their shared learning goals. Meanwhile, *tensions* refer to the failure to realize epistemic alignments such that one domain's goals become overshadowed by the other.

With a focus on supports and constraints for IIR, this study asks:

> How do the synergies and tensions at the intersection of data science and the arts support or constrain opportunities for students' engagement in IIR practices, including "going beyond data," "using data as evidence," and "evaluating and expressing uncertainty about generalizations"?

By examining IIR in terms of disciplinary synergies and tensions, this study aims to describe the opportunities and challenges of arts-integrated approaches to data literacy instruction. Our findings contribute to theoretical conceptualizations of data literacy learning and of integrated disciplinary learning, as well as practical recommendations to guide educators and designers of similar learning experiences.

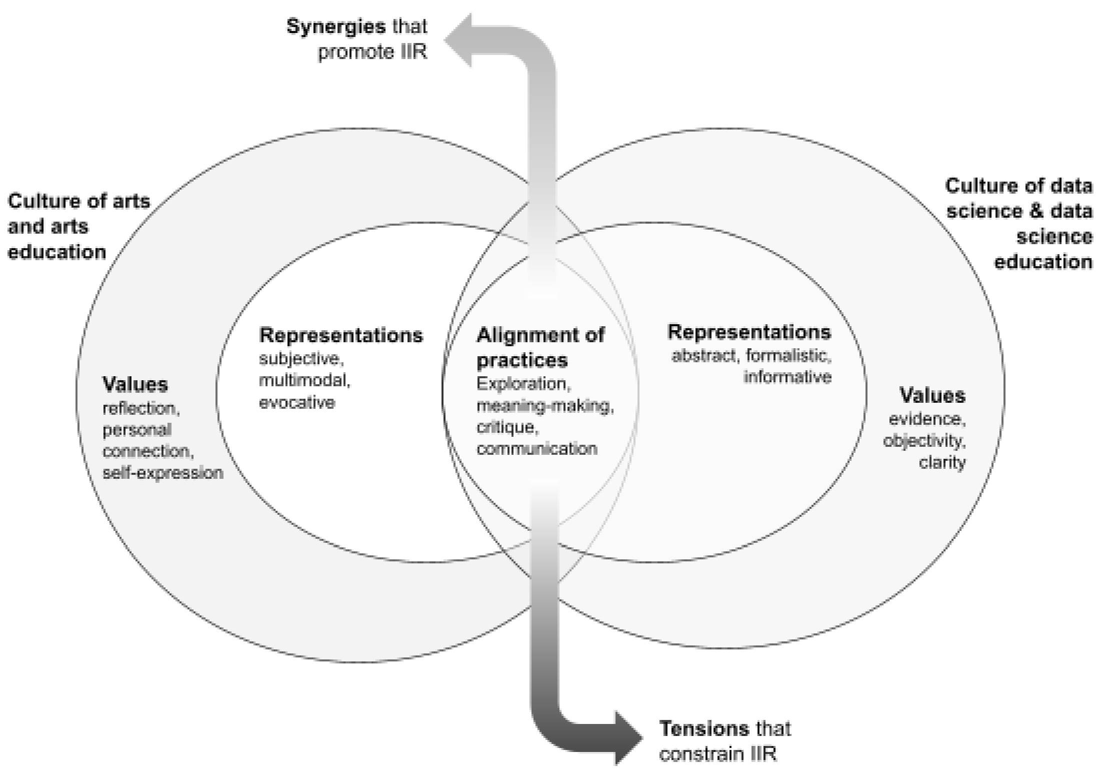

Figure 1. The intersection of arts and data science cultures can create synergies or tensions that promote or constrain IIR.

Methods

Participants and context

The co-authors of this study include faculty and graduate students, who are team members of a project funded by the National Science Foundation (NSF) to promote middle school students' data literacy learning through the arts. At the time of writing our proposal to the NSF, we recruited 10 teacher participants to co-design the project's curriculum with us: Two teachers from each of four schools (1 public charter, 1 private, and 2 public schools, across three states in the United States). These teachers were recruited from among our personal and professional networks, based on their expressed interest in teaching across disciplines by incorporating data science literacy into their arts curricula, or vice versa. The teachers were experienced in their subject domains, with 5-10 or more years of classroom teaching experience, but all were new to co-design and to arts-integrated data literacy education. The four schools served diverse student populations that varied from 2-65% white and 25-95% non-white students, and 40-86% in economic need as defined by eligibility for free and reduced price lunch. Each of the classrooms in which we implemented the units included 15-30 students.

Unit designs and implementation

In school-specific teams that each included at least one math, one arts teacher, and two researchers, we co-designed and supported teachers' enactment of four units (1 unit/school) with integrated arts and data literacy learning goals (Table 2): *Dance*, *Photoessays*, *Comics*, and *Collages*. Except for *Dance* (whose teachers had made alternative curriculum commitments), we supported a second iteration and enactment of each unit in the subsequent year of our collaboration, and include data from those second implementations in our current analysis.

The four unit designs emerged from our co-design process with teachers, in which we sought to align our larger project's overarching goal to address data literacy learning goals through the arts with each teacher's curriculum goals, student interests, and classroom resources. The resulting units ranged from 2 weeks to 1 semester long. While they varied according to teachers' circumstances, we ensured that each unit shared the following features, based on our conjecture that they would promote students' engagement in IIR through the arts: (1) A driving inquiry question grounded in a personally- and socially-relevant issue; (2) a student-generated or public dataset to enable students to use data respond to the driving question; (3) a prompt to use an artistic medium to communicate a claim or perspective based in a critical interpretation of data; (4) a prompt for students to write an artist's statement to explain the data-based claim, and to rationalize their artistic choices. These common elements and the variations that emerged as teams identified overarching questions, datasets, and artistic forms and materials) provided an opportunity to examine how and the extent to which data-art inquiry engaged students in IIR.

More specifically, in a *Dance* unit, students choreographed and performed dances that communicated a claim developed based on their examination of graphs on various socio-economic and environmental issues (labor, gender inequality, environment). In a

Photoessays unit, students used photography and creative writing to personalize and critique standard indicators of community health. In a *Comics* unit, students created graphic narratives, in which they reflected on how their personal friendship experiences related to their findings from a grade-wide survey on friendship, as well as PEW Research data on Teens and Technology. In a *Collages* unit, students created collages from found digital imagery to represent their personal time use in relation to findings from the American Time Use Survey (bls.gov/tus). For further details of the unit designs and implementation outcomes, see Authors *et al.,* (DATE).

Table 2. Brief descriptions of the four data-art inquiry units.

Unit Integrated subjects *School*	**Description**
Collages ELA | Math *Public urban school*	**How can we use collage to make data-based arguments about personal time use?** Students critiqued informational texts and analyzed public data about time use, and produced digital collages with found imagery to communicate arguments about what their own personally-collected time use data says about them.
Comics Visual Art | Math *Public urban school*	**How can we use comics to reflect on our own friendship experiences in relation to others?** Students analyzed graphs of their own and their peers' responses to a survey about friendship beliefs and experiences (e.g., Which best describes you?: I can count on my friends when things go wrong. I find it easy to make friends, etc.). They created digital comics to convey personal reflections about their own experiences in relation to their class data.
Dance Dance | Math *Suburban charter school*	**How can dance be used to communicate meaning behind data?** Students interpreted data visualizations on issues of their choice (e.g., employment, environment, addiction), then choreographed dances to communicate about those data and their inferred implications.
Photoessays ELA | Visual Art | Math *Private urban school*	**How can we use photography to engage critically with public data around the question: 'What contributes to a healthy neighborhood'?** Students critiqued existing indices of healthy places, then used photography and creative writing to document and convey their personal perspectives on indicators of the health of their own communities.

Data sources and analysis

Our research data include (1) post-implementation interviews with each of the 10 teachers. These 1-2 hour-long semi-structured interviews focused on eliciting teachers' reflections on the challenges and successes of the units, their observations of student learning, and their ideas for improving the unit. (2) Teacher-generated artifacts, including presentation slides, exit tickets, and written post-class reflections. (3) Student-generated artifacts, including their data artworks and artist statements (e.g. Figures 1-4). (4) Interviews with 3-4 focal students per implementation, which asked students to reflect on their processes and artistic decisions, and to explain the connections between their artworks and their interpretations of the data.

To develop our analytic framework, our research team engaged in a process of collaborative qualitative data analysis, which prioritizes the integration of multiple diverse perspectives—both those of individual team members, and of different theoretical stances—into the interpretation of data (Schielke et al., 2009). This process recognizes the value of consensus among multiple team members as an indicator of reliability in data analysis, which can be as robust as inter-coder reliability among two researchers, and more robust than if an idea were advanced by a single researcher (Morrow, 2005). We chose this approach because the aim of our analysis was to test the limits and possibilities of an emerging framework, and not to make claims of representativeness, for which conventional approaches to, and measures of interrater reliability (e.g., blind independent coding and Cohen's Kappa) would have otherwise been better suited.

To ensure reliability in our analysis, we divided our larger team of researchers into subteams, which each led analyses of data gathered from implementations of individual units. Each researcher served on two subteams. We vetted and developed ideas through iterative cycles of independent analysis by subteams, and discussion among our large team. To ensure the inclusion of each team members' perspectives, we initially wrote individual memos shortly following the implementations of the units. These were written in a shared document, structured with prompts that we had designed to elicit our ideas on the challenges, opportunities, and distinct data-art practices we each observed in our work with participating teachers and students (see Authors, DATE for the prompts). These memos served to initiate our ongoing subteam and whole team discussions as we first analyzed implementation-specific data, then synthesized across those findings to develop our current, broader conceptualization of the role of the arts in data literacy education.

The results presented here come from our iterative subteam and whole team discussions of our entire project data set. From these data, we followed a purposive sampling approach called maximum variation sampling (Etikan *et al.*, 2016) to identify examples from students' work to demonstrate aspects of our framework. Rather than attempt to describe a representative student experience, this approach seeks examples that are most illustrative of a framework, both by showing the ideal, and the non-ideal experiences. In doing so, this analytic approach helps to define and test the utility of a framework for explaining a phenomenon.

For this study, we nominated examples of student work that either illustrated students successfully, or less successfully, going beyond data, using data as evidence, or expressing uncertainty, as defined by Makar and Rubin's (2007) framework for IIR. Through further discussion among our whole research team, we identified the aspects of data-art integration that appeared to support or hinder IIR. We particularly sought to define these aspects in terms of tensions and synergies created at the intersection of disciplinary cultures and their traditional representations, and to use these to explain how they supported or hindered students' IIR. An example of successful IIR created by a disciplinary synergy is one in which students articulated an IIR practice through an artistic practice (e.g., making aesthetic choices that would evoke an emotional response to a data claim). An example of a less successful IIR is one in which students' engagement in an arts practice was at the expense of their effective engagement in an IIR practice (e.g. students abandoning attempts to make artistic choices based on accurately conveying a data claim, in favor of what they personally find to be aesthetically appealing).

After identifying these examples, we compared them in terms of the unit designs that supported their creation, the classroom context of the unit's implementation, the students' personal experiences in creating those examples, as relayed to us by their teachers. This final step allowed us to elucidate the potential role of the context of our implementations in shaping the disciplinary synergies and tensions, and the IIR we observed in students.

Notably, some of the examples we identified demonstrate various synergies and tensions across multiple aspects of our framework. For instance, one example may at once illustrate students using aesthetic representations and integrating their personal experiences (two data-art practices that we identified in our analysis) to convey a particular emotional tone in communicating data-based predictions as they "go beyond the data." The fact that one data-art practice can facilitate more than one IIR practice indicates the many opportunities that data-art inquiry offers for engaging students in IIR.

Likewise, the same example might at once illustrate both a disciplinary synergy that facilitates an IIR practice, even as it illustrates a tension that constrains a different IIR practice. Such overlaps in practices are expected—and welcome—in interdisciplinary work (Reynante et al., 2020). Moreover, the fact that one data-art practice can potentially illustrate many kinds of IIR is indicative of the various learning opportunities that data art inquiry offers engaging students in IIR.

For clarity, we limit the presentation of our results to those examples that, in our estimation, best illustrate the most distinct affordances and challenges of data-art inquiry for supporting IIR. We also include these examples because they contribute to the whole of our results by illustrating the range of different data-art inquiry approaches and outcomes observed among our student participants.

Results

Here, we describe examples from across our data, selected to best illustrate disciplinary synergies and tensions as they promoted or hindered IIR. For a synthesis of our findings, see Table 3.

Table 3. Disciplinary synergies and tensions that promote or hinder IIR practices (Makar and Rubin, 2007).

IIR Practice	Contributions of the arts to data literacy learning	
Going beyond data by making generalizations, explanations, predictions about populations, mechanisms, or contexts that are broader or different than the sample of collected data.	**Synergies** + Generalizations are informed by personally and locally relevant experiences, and used to reason about the meaning of data, and its social and environmental implications. + Construct claims by connecting lived experiences to aggregated data. + Artistic forms (e.g., image, narrative, movement, embodiment) and techniques can concretize and center context and social and environmental implications of data (in contrast to abstract representational forms).	**Tensions** - Challenges arise with expressing local/personal perspectives that are in discourse with broader patterns evident in the data. - Domain differences exist in valuing subjectivity vs. objectivity, and in the kinds of data and claims considered to be more/less valid. - Domains differ in the place that personal and social issues have in learning.
Using data as evidence by representing data and explaining data reasoning.	**Synergies** + Data include qualitative as well as quantitative values (e.g., numbers, text, images). + Artistic approaches enhance ways to generate, communicate, and represent data. + Artistic materials and forms center context and embodiment in data representations	**Tensions** - Challenges relate to simultaneously representing and balancing both 'local' and 'global' perspectives of data through the materials of specific art forms. - Students must navigate multiple disciplinary ideas about what counts as evidence and what priorities should drive representational choices.
Expressing uncertainty by qualifying generalizations with probabilistic language.	**Synergies** + Arts component allows for emphasis on engaging with multiple perspectives or data stories throughout data inquiry. + Acknowledge and represent the non-neutral nature of data inquiry and visualizations. + Uncertainty can be visualized and embodied through artistic characteristics as well as through language.	**Tensions** - Conventions for mapping meaning onto artistic representations are not pre-determined as they tend to be in conventional data representations, which can present challenges in choosing and interpreting representations. - Allowance of subjectivity in both the creation and interpretation of data-art can lessen creators' control over their message.

How disciplinary synergies promoted IIR

Going beyond data: Contextualizing data through visualized or performed narratives

The narrative or performative art forms of dance, comics, photo-essay, and collage, each offered unique affordances for supporting students in *going beyond data*. In the *Dance* unit, one group of students choreographed a dance based on a line graph visualizing e-cigarette use among teens. The students used their body positions to create an embodied quantitative comparison between two groups and choreographed their movements to represent how the data changed over time. However, the students also went beyond describing data by physically representing the likely outcome of using e-cigarettes: The dance ended with all students laying still and lifeless on the floor. Thus, dance offered a physical language with which students could both describe a numerical trend and narrate the possible health impacts on teens.

In the *Photoessays* unit, one student composed a series of photographs that highlighted construction as a potential contributor to lower air quality in her neighborhood (Figure 2). After selecting air quality data from a public map-based data visualization tool and making a scatterplot to explore the relationship between air quality and average life expectancy, the student *went beyond the data* by using photography to highlight a potential explanation of lower air quality observable at the street level of her neighborhood. To construct her photo-essay, she chose to photograph a construction site she passes everyday to school. Her series used patterns to represent the frequency of exposure she experiences in her daily routines and her broader claim about the prevalence of construction in her neighborhood over time. In her artist statement, she explained her compositional choices, such as framing, use of line, and repetition, to "shine light on these neglected endangerments" and "show my perspective of seeing construction in my daily life." This example demonstrates how data storytelling through photography can help students to contextualize quantitative patterns in their personal experiences, and to communicate potential explanations for those patterns.

Students' artist statement: "I grew up with the thought that construction is usually the cause of traffic. While that's true, I wasn't told much more about the dangers of it. Other than the worsened transportation, most sites go overlooked until a building or bridge is officially created and advertised. With construction being the normality in this borough, the damage it causes lives in a shadow behind 'more important' issues. Construction isn't deemed to be important to many people, yet causes decreased air quality that is capable of damaging lungs and increased harsh sounds that contribute to noise pollution. My goal for this photo series was to shine light on these neglected endangerments.

Everyday, to and from school, I pass by a bridge that is constantly under construction and next to it, a building that is in the works of being finished. I realized that I never really paid much mind to it because it's normal for places to be under construction. No harm can come from it, in fact we are gaining a better bridge and building, right? Then I thought more about it and came to a conclusion that although it looks like not much damage is occurring, there is always more than meets the eye. We aren't able to see the air quality changing, but it does. The average microgram per cubic meter of fine particulate matter is 7.2 where I live. Then we passed by cranes and drills that I used for capturing the noise that came from construction. It is also important to have greenery in a healthy neighborhood and the places that are a great opportunity for this are being occupied with being the home to construction materials.

Throughout my journey of creating my photo essay, I tried to focus also on what was visually appealing. I used the bridge lines to divide parts of my pictures. Construction sites use a lot of bright orange cones and blockers that I wanted to incorporate in my photos to add color. I took the pictures in my car and used the window frame to show my perspective of seeing construction in my daily life."

Figure 2. This students' photo-essay uses photography techniques and verbal narrative to connect her lived experiences to aggregated data, and to spotlight an environmental issue in her neighborhood.

In the *Comics* unit, one student created a comic using the online comic-creation platform, Pixton, to reflect on issues teens experience related to friendship, such as bullying on social media. The student selected data about how often students in their class experienced drama on social media from a class-wide survey completed at the beginning of the unit. Their comic (Figure 3) introduces this issue by showing an interaction between three friends: Two boys notice that their other friend is sad and discover that he was bullied on social media. The two boys respond empathetically through their dialogue and gestures. However, one of the boys researches this issue further, finding a statistic about bullying on social media. The character *goes beyond the data* by using this statistic to alleviate his friend's pain, pointing out how the statistic shows that a lot of other teens have experienced a similar kind of bullying and that it is not an isolated event. Drawing on data enabled the friend to not only individually express empathy but suggest that there is a broader population of their peers who would likely empathize with this experience. In this case, the strategy helps the friend distance himself from the negative experience and re-engage in social media with a new perspective. This connection between the use of data to reflect on how one might manage their emotions was not just enacted through comic narratives, but in the way student authors reflected on their reasoning process. For instance, one student shared:

> "This made me see that I'm not the only one that's struggling and it's okay because there's still kids that are going to find it easy and they're going to know how to become your friend properly. It shows that basically everyone has a little bit of trouble for the most part and I'm not alone when it comes to how I view making friends."

Figure 3. One student's data comic on online bullying and frequency of drama.

Using data as evidence: Representing data in context through composition and movement

Integrating art and data challenged traditional disciplinary ideas about what kinds of data (e.g., numbers, text, photographs) count as evidence and how to communicate data as evidence. In the *Photoessay* unit, students shuttled between taking photographs and engaging in statistical inquiry (i.e., asking statistical questions, analyzing data, and visualizing data) to investigate social and environmental issues in their neighborhood. Photography motivated students to reason about different types of data (i.e. qualitative and quantitative data) at different levels of aggregation (e.g., street vs. neighborhood) to construct data stories. Furthermore, artist statements which accompanied artworks in presentation, enabled students to reflect on their lived experiences and how reasoning about data, in some cases, shifted their perspectives. As one student remarked:

> "I never really paid much mind to it because it's normal for places to be under construction. (...) Then I thought more about it (...) We aren't able to see the air quality changing, but it does. The average microgram per cubic meter of fine particulate matter is 7.2 where I live…"

An arts-integrated approach to data visualization also offered unique ways to contextualize data. For example, in the *Dance* unit, students choreographed dances that not only compared groups along categorical variables but physically embodied features of these groups (e.g., movements like those of a bird or a fish). In one dance, students contextualized human's exploitation of animals through a "trust fall" (Figure 4): One dancer, embodying animals, falls into the arms of another dancer, embodying humans, as a metaphor for animals' reliance on—and thus need to trust—humans to help them to survive. As one student explained, using dance to both represent and interpret statistical ideas, "made us look at the graphs in a different way. Like at all angles to figure out what is the best view we can get of this graph to make movements to help others understand what is happening."

Figure 4. Two students doing a "trust" fall in their final performance of their choreography, based on their examination of an animal population graph.

Expressing uncertainty: Critically engaging with how data are produced and used

Students demonstrated engagement with the inherent uncertainty of informal inferences by raising critical questions about generalizability and by representing multiple perspectives on data or possible data stories. In the *Comics* unit, for example, one student created a comic that reflected on class-wide data on a survey item, "*How easy or hard it is to make friends?"* (Figure 5). The main character is a comic book version of herself speaking directly to the readers, and engaging with potential uncertainties in the data by reflecting on her own friendship history. She notes that all her friends were made at such a young age that she cannot remember what it was like to make new friends. She wonders whether her experience "matters" in how to interpret the survey result given these potential unaccounted variables ("when and how you met your friends," and people's abilities to recall those experiences) and questions whether the data is generalizable for her. In this example, the dialogic, character-centric format of the comic, facilitated this students' personal reflection on the data, encouraging her use of personal experiences to identify hidden variables and question the validity of the survey data.

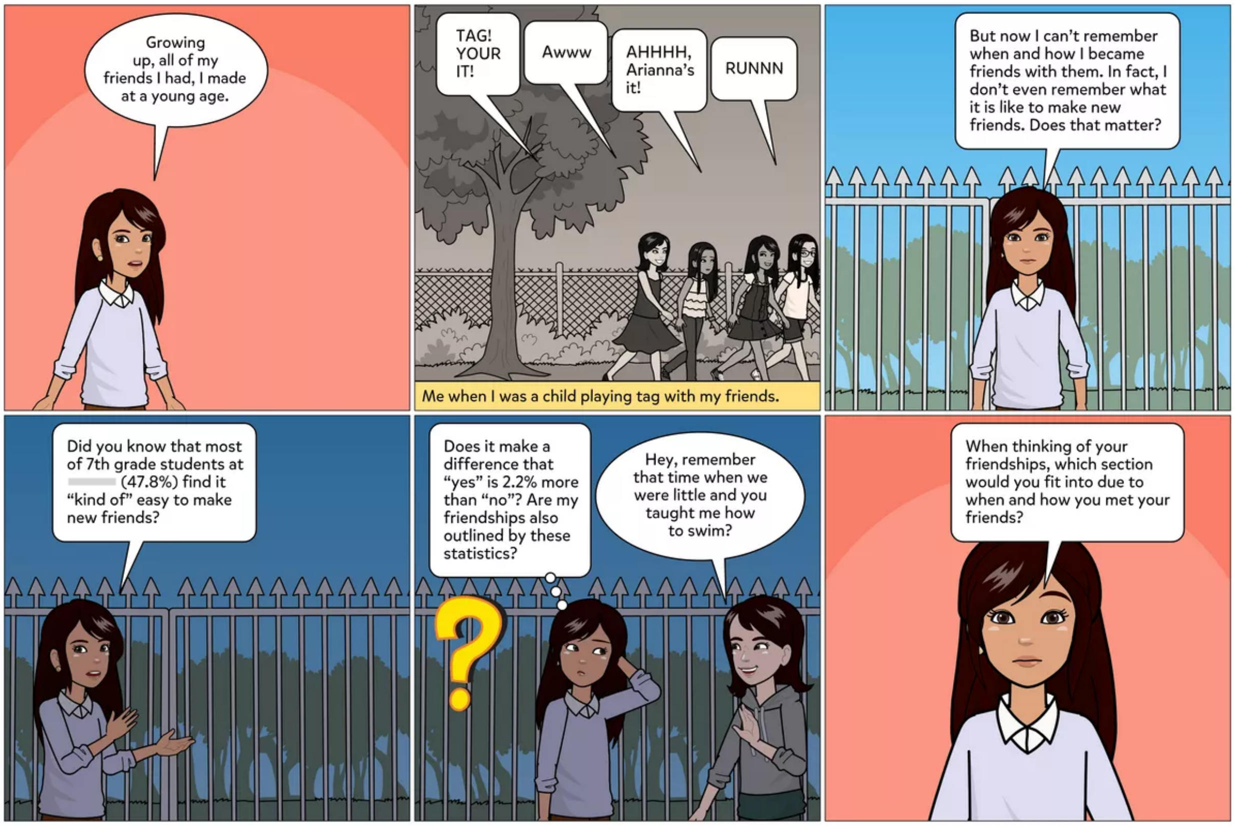

Figure 5. Example of a comic made by a student from the *Comics* unit.

In the *Collages* unit, students created collages to represent how teens spend their time and how time use impacts their well-being. The whole class engaged with uncertainties inherent in making informal inferences about a population (i.e. teens) from a sample (i.e., class-wide data) by asking questions such as "how would this data look different for students living in California?" Notably, planning visual associations between time use and wellbeing in making their collages surfaced students' own assumptions about how they see themselves and others (Figure 6). For instance, one student challenged claims that people have agency over their time use, positing that time use among youth is less of a choice than it is for adults. Another student reflected on how assumptions about people based only on their time use can misrepresent who they actually are, and limit their possibilities for growth. Such discussions led students to question what other data might be needed to best reflect who and why a person is who they are.

It worked well for him, because he knew the reason why we were making it he knew that it had to be based in rooted in data, his own data, how do I spend my time, how does it make me feel…
-ELA teacher

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"She changed her argument halfway through the second day and she was like maybe as we get older these things become a choice, like you don't always have to engage in the things that make you feel depleted and sad and you know all those things are still going to be there, but maybe it becomes a choice.
-ELA teacher

Figure 6. Two student-created collages alongside reflections on their work shared by their teacher during the post-implementation interview.

How disciplinary tensions constrained IIR

Going beyond data: Missed opportunities to integrate disciplinary practices

While there were many promising ways that art and data science synergized to support IIR, there were also ways that these domains created tensions that constrained IIR. Leveraging art to contextualize patterns, consider implications, and draw connections to students' lived experiences required shuttling between domain-specific practices and routines that were part of different classroom cultures. However, some students demonstrated over-reliance on either artistic or mathematical practices and values common in their classrooms. In the first iteration of the *Collages* unit, for example, we had initially planned for concurrent ELA and Math classes to engage students in complementary perspectives on data from the American Time Use Survey (bls.gov/tus). However, unforeseen testing requirements disrupted this schedule so that students first completed an ELA-only unit, then a Math-only unit, using the same focal dataset. As a result, discussion of big ideas about data (a typical practice in ELA), and support for graphing and data analysis (typical practices in Math), were contained in separate classrooms, rather than integrated. When students in the Math class began to question the relevance of data to their lives, teachers, lacking preparation to facilitate these critical discussions, missed opportunities to help their students go beyond the data by, for example, examining the role of sampling in informal inferences or the social implications of potentially under-representing some groups of people. On the other hand, while such questions were explored in ELA, the discussion of data remained broad and conceptual rather than tied to a specific data set and analysis.

Another type of constraint emerged from teachers' concerns about facilitating discussion around social issues. In the comic unit, for example, teachers were concerned about the kind of discussions and personal reflections that might emerge from exploring the topic of friendship. One consequence was that data on some variables (such as cyberbullying and race) were left out of the data set, and in turn, from the data visualizations students analyzed. Ultimately, students spontaneously addressed topics of cyberbullying and race in their comics, demonstrating the personal relevance of these issues to their lives, but also showing how neglecting these variables limited the kinds of informal inferences students could make about them. While the art teacher felt comfortable connecting disciplinary concepts to personal experiences, the math teacher was prompted to adjust her pedagogical approach, and shared, "I felt like it was just a positive experience for me because I don't always get to talk to them about, you know, things that are more relatable."

Furthermore, the integration of personally-relevant data also introduced tensions in how to reconcile personal experiences with broader trends, and the impact of such connections on broader claims that can be made. The ELA teacher of the *Collages* unit, for instance, noted in her post-implementation interview that many of her students "weren't creating collages based on data [from the American Time Use Survey, or sampled from their personal time use]. They were creating collages in an attempt to send some kind of message about teenagers in their lives, and how they spend their time and how they feel." While this in itself is a valuable endeavor, in an arts-integrated IIR learning context, it also demonstrates the need to engage students with models of data-art that effectively integrate both personal and broader experiences evidenced in data.

Using data as evidence: Missed opportunities to connect artistic choices to a broader narrative based on data

Differences between data science and the arts in terms of the kinds of evidence valued in arguments, were especially apparent in the *Collages* unit. When her math teacher colleague dropped out of the study, the ELA teacher led both the math and the ELA components in a second implementation of this unit. Students collected self-reported data about how they spent their time over the prior week (i.e., activities, time on task, mood) and collectively created three data visualizations of time spent engaging in different kinds of activities (i.e., leisure, work, outdoor time). While the ELA teacher supported students in identifying data points, clusters, and patterns in a data visualization intended to be used by students as evidence of their claims, she generally prioritized categorical data and descriptive analysis, typical of common ELA activities, such as identifying evidence in news articles. Thus, students received less support in engaging with more formal mathematical concepts and practices, such as representing proportions and distributions. Their collages reflected this emphasis by communicating broader themes of their investigation, but lacking numerical representations or explanations. There were thus missed opportunities to engage with critical perspectives about data using the affordances of collage to integrate images, text, and numbers.

These different disciplinary priorities were also reflected in students' tendencies to allow aesthetic preferences, rather than data, to drive their artistic decisions. A student in the *Dance* unit, for example, reflected: "We wanted to do (dance) movements that didn't always go with the graphs," but instead, "just kinda looked cool." Students also negotiated tensions between embracing subjectivity, which tends to be valued in the arts; and conveying clear messages, which tends to be valued in data science. For some students, audience considerations were central to supporting their representational choices. For example, in the *Dance* unit, as students planned how they would create embodied representations of the data, they questioned and examined the perspective of the audience, including how the audience would interpret and engage with their dance and the information they were communicating, as well as the feelings that they wanted them to experience. One student reflected on their data dance creation process, sharing:

> "Some pieces we did change because when I was choreographing the dance, I like knew what was happening and what it was supposed to represent, but we really had to think about… how to make it easier to understand for those who haven't watched it a bunch of times"

This example demonstrates the challenge for students to communicate claims clearly in a medium that is so open to interpretation. Yet at the same time, this example shows how students recognizing the possibility for multiple interpretations, and desiring to balance these with a clear message, assumed the perspectives of an audience to critique their own work, and to inform refinements to their representational choices.

While some students across all four implementations successfully realized this disciplinary synergy, and could connect aesthetic values, art elements, composition strategies, and stories to informal inferences, others struggled. For instance, in the *Collages* unit, the messages in some students' artworks primarily emphasized the emotional consequences of time use and only weakly incorporated data-based evidence. Meanwhile other students' artworks only superficially commented on things that they liked and disliked. In these cases, students' familiarity with typical art class collage and self-portrait assignments may have led them to overlook the prompt to use these to connect data to a claim.

In the *Photoessays* unit, some students relied too strongly on feeling "inspired" to take pictures, missing other opportunities to connect images with quantitative data about their neighborhoods. One student reflected on this tension between inspiration and using photography as a form of inquiry in his artist statement: "I was ready to go outside and find some inspiration to create a story of some kind with my pictures, but as big as my neighborhood park is, there was only one thing that made me inspired to take pictures…" The final photo-essay demonstrated the result of not addressing this tension. The essay begins by discussing statistics on access to parks and the student's process of inquiry, but shifts abruptly to a more poetic, conceptual analysis in order to explain and justify the photographs the student was "inspired" to take. While the essay explores a clear theme, the overall message and informal inference is ambiguous and not fully supported by data.

Expressing uncertainty: Grappling with uncertainty in both data and art

In recognizing the inherent uncertainty of informal inferences, students are ideally challenged to ask questions about how data are produced and used (e.g., who collected the data, for what purpose, what is not represented by that data?) instead of disregarding data that does not align with their lived experiences or citing inferences as neutral, objective facts.

In the *Comics* unit, for example, some students identified gaps in their class data set, highlighting variables such as race and other aspects of identity as important for understanding how teens make friends and for reasoning about the statistical interpretations within their data. When explaining their certainty regarding the data, one student responded:

> "I feel like [the survey should consider] bullying and maybe something close to friendships with how you make the friendship in life when it works out. For example, if you're maybe a person of color it could be difficult for you to make friends, or if you have a disability or reasons why you might be excluded or reasons why you might not feel like you can make friends."

Thus, students identified gaps in available data (e.g., the absence of data on race), which introduced uncertainty about their inferences. They questioned whether it was possible to make valid informal inferences with the dataset without being able to explore how patterns in the aggregate might differ by student background. In turn, students struggled to use the Comics format to both convey a clear inference, while also conveying their uncertainty about it.

Discussion

Data-art inquiry practices and instructional recommendations

We sought to explore how integrating data science and the arts enabled or constrained opportunities for students' IIR. Often, traditional graph-based representations accompanied by a verbal narrative are adequate to support in IIR. Yet, we argue that arts-integration prioritizes a humanistic perspective on data that allows students to incorporate the personal and contextual knowledge necessary for IIR (Bhargava *et al.*, 2015; De Veaux, *et al.*, 2022; Gebre, 2022; Madison, 2002; Philip *et al.*, 2013; Rubin, 2005, 2021; Scheaffer, 2001; Steen, 2001; Vance *et al.*, 2022; Wolff *et al.*, 2016).

Below, we posit four data-art inquiry practices observed to support or constrain students' engagement in IIR, along with instructional recommendations for amplifying the synergies, or addressing the tensions observed between domains.

1. Use visual or performed narratives to contextualize data relationships

While students' used narrative to engage successfully in certain aspects of IIR, some students struggled to integrate data science ideas, such as uncertainty and evidence, into a narrative form.

In terms of promoting IIR, we observed how narratives offered structures for elaborating on the context of data (Zohar & Nemet, 2002), and for communicating generalizations, explanations and predictions with data. For instance, in the *Comics* unit, students used narrative structures of conflict to explain the expected and apparent messages in the data; and concretized abstract data relationships through relatable examples (e.g., social interactions among characters). In the *Dance* unit, students made intentional decisions about how to re-represent relationships observed in graphs using time, space, movement, music, and dancers' roles; and moreover, how these elements of dance would impart an emotional quality to those relationships portrayed, effectively communicating their evaluation of their real-world implications. In the *Photoessays* unit, one student proposed a relationship between low air quality observed in public city data, and the abundant local construction observed in her neighborhood, captured in her photo series. Such examples are notable because of how contextualizing data can support informal inferences, the understanding of real-world applications of statistical concepts such as multivariate analysis (Makar et al., 2011; Pfannkuch, 2011); and can also seed discussions of what further data investigations could be conducted to test hypotheses.

At the same time, narratives tend to afford telling a singular or limited set of perspectives. Conversely, a conventional data-based argument describes aggregated perspectives apparent in data patterns and trends. We aimed for learners to embrace both the single and aggregate perspectives. However, achieving this balance was challenging, particularly as students were still navigating the constraints and affordances of specific artistic materials and forms.

Recommendations. Contextualizing data in narrative can be a powerful way to concretize abstract ideas about data, but it can also lead students to focus on individual stories instead of aggregate data patterns. Curriculum designs can help learners to take advantage of narrative to support contextualization of the data by offering templates of narrative structures and techniques for communicating about data, and a discussion of their limitations. These templates might scaffold strategies for integrating single and aggregate perspectives, comparing among contrasting perspectives, and juxtaposing complementary datasets. For example, Bach et al. (2018) identifies design patterns for data comics, which use features such as panel order and layout for data-driven storytelling.

2. Draw on personal experiences to engage with uncertainty in relating local to global data

In this data-art inquiry practice, learners go beyond the data to grapple with issues of evidence and certainty in relation to their personal experiences (D'Ignazio & Bhargava, 2016; Gutiérrez et al., 2020). In the *Photoessays* unit, learners localized their investigation of a data topic in a familiar context (their neighborhoods), and used their experiences living in those neighborhoods to identify gaps in data that contribute to its uncertainty. Meanwhile, *Collages* students, reflecting on their own and others' time use, wondered about the degree to which people have agency in the activities they choose. This led students to question the certainty with which global conclusions could be drawn about time use data, a theme that ultimately appeared in some students' artworks.

While an arts-based approach to data can support engagement with bigger ideas in data science, such as uncertainty, it also risks leading students to overemphasize subjective and personal experiences at the expense of grounding their ideas in data. For example, some *Collages* students developed artworks about how they would like to spend their time, rather than to communicate data about their current time use. Such examples resonate with other literature, which finds that contextual information in statistical problems can sometimes mislead students, causing them to magnify their personal experiences relative to aggregated data-based evidence and broader patterns in data (Konold, et al. 2015; 1997; Lee and Wilkerson, 2018).

Recommendations. Curriculum designs might support students' reasoning about local and global data by guiding their reflection on how their personal experiences relate to these data. Such guidance might involve prompts to consider how variations between local and global patterns might correspond to concepts of sample representativeness and sample variability (Rubin, 1991). This guidance might also support learners' appreciation of the implications of uncertainty in such data For example, students might be prompted to use their personal experiences to identify missing or "counter-data" (D'ignazio & Klein, 2020), to consider how these gaps contribute to the certainty with which conclusions about these data can be drawn, and how they contribute to misrepresentation of the populations described by the data (D'Ignazio and Klein, 2020; Lee et al., 2022). In this manner, students' personal experiences might begin conversations about the significance of data at a societal level.

3. Use aesthetic representations to elevate emotion in communicating about data

In this data-art inquiry practice, learners are intentional about using their data art to emphasize the lived experiences of the people reflected in the data. Students in our study used characteristics of their artistic media, such as collaborative choreography in *Dance*, and interactions among characters in *Comics*, to represent the human dimensions of data even as they communicated statistical ideas, such as uncertainty, trends, and group comparisons. These dimensions enabled learners to convey emotions through how their characters felt in the *Comics*, and within how the message was conveyed in the choreographic choices in Dance. This practice resonates with a data feminism principle that d'Ignazio & Klein (2020) call "elevating emotion."

However, artistic data representations can conflict with data-driven choices. These tensions can become more pronounced when disciplines differ in what counts as evidence and what priorities should drive representational choices; and when learners shift from using canonical data representations, which have established conventions for symbolizing ideas about data, to imagining novel artistic representations to both communicate data ideas, and to elevate emotion. For example, some *Dance* students chose particular dance moves because of their aesthetic appeal, not because they would serve a data-based argument. Similarly, some *Photoessays* students sought to collect certain photos that were visually interesting, even though they were unrelated to the subject of their data; and some *Collages* students chose to include certain imagery in their collages because these were related to the broader theme of their investigation not because they illustrated any pattern interpreted in their dataset.

Recommendations. One recommendation for supporting learners in adopting this data-art inquiry practice is to establish clear criteria for what counts as evidence with respect to the values of each domain. These criteria could be illustrated with models to demonstrate various ways that artistic media can be used to communicate particular arguments with data. Students could examine professional examples of data art in terms of the perceived effectiveness of different techniques at conveying data claims and evoking particular emotions, and use these as inspiration for their own data artworks. Templates of common techniques might also be provided, which students could modify according to their own goals.

Another recommendation is to incorporate the writing of artist statements. Artist statements are used by artists for self-analysis, but also to convey to audiences their intentions, approaches, and reasoning (Fallon, 2019). In our study, students additionally used artist statements to describe how they analyzed and interpreted their data, the data-based argument that they aimed to convey, and the impact they intended to have on their audiences through their artistic choices.

Finally, assessment strategies should be devised early during unit planning, with consideration for what disciplinary, interdisciplinary, or transdisciplinary learning goals are intended, and for what would be satisfactory evidence that learners have achieved those goals (Gao, et al., 2020). Artist statements can be useful assessment artifacts, as they reflect students' reasoning and understanding in ways that are implicit in their final products. Artist statements also monumentalize the process of data art creation, and so address criticisms that STEAM overlooks the importance of the creative process in favor of the final product (Perignat, 2019).

4. Use audience considerations to reflect on the non-neutrality of data

In this data-art inquiry practice, learners use their audiences' likely interpretations to refine their artistic choices. This exercise can prompt reflection on the inherent subjectivity of both art and data. It can also encourage recognition of how, through messaging, data can be used and misused in arguments. For instance, students in the *Dance* unit put themselves in their audience's shoes to help evaluate the clarity of their message, and to iterate on their choreography accordingly. In the *Collages* unit, students reflecting on the stated purpose and application of public time use data, proposed that agency over time use may be different among teens than among adults, so that arguments based on time use will be more or less valid, depending on the audience to whom they are intended to apply. Recognizing the non-neutrality of data is especially relevant as youth increasingly encounter complex social issues that require reasoning about data, and understanding it from multiple perspectives (Gutiérrez et al., 2020). Data science and the arts invite different degrees of subjective interpretations and critical questioning of data-based evidence.

Recommendations. Peer critique can support learners in this data-art inquiry practice, Critique is a discussion format through which groups of artists reflect on peer (or professional) work. Critique can be used to analyze and learn from artistic choices. It can also allow artists to test whether their choices are having the desired audience impact. By observing an audience's reactions to, and interpretations of a message, learners can determine whether the perspectives and stories they intended to convey are apparent to others. Critique can furthermore be a valuable opportunity for formative feedback, as learners can use audience feedback to iterate on, and refine their artwork (Hetland et al. 2015).

Theoretical contribution

This work connects to several existing theories and frameworks in data science education that similarly seek to expand on learners' informal inferential reasoning skills. One notable connection between a data-art inquiry approach and a feminist approach to data science (D'ignazio & Klein, 2020), whereby art can serve as a means for personal self-expression and for wrestling with issues of subjectivity. By elevating emotion and embodiment, rethinking binaries and hierarchies, and considering contexts—each of which are principles of data feminism—the data-art inquiry approach has learners engage in IIR in ways that emphasize the power relations inherent in the generation and use of data. Concurrently, the data-art inquiry approach joins other efforts to take more humanistic approaches to data science. Data-art inquiry practices may serve as a way to collapse the distance between what Wilkerson & Lee (2021) describe as the personal and cultural layers of data practice. Students' taking on artistic approaches to visualize data can further challenge disciplinary values in data science, which in contrast, have historically minimized the value of context, emotion, and subjectivity. Lastly, a data-art inquiry approach connects with Halverson's (2021) notion of learning *in* the arts (e.g., learning about pottery in a pottery class) and learning *through* the arts (i.e. learning about Ancient Greek culture and mythology in a pottery class). Our findings suggest that, at least with an already interdisciplinary field of reasoning such as IIR, it is worth not only considering how students might learn about data "in: and "through" the arts, but "in synergy with" the arts.

Limitations and future work

Variation in support for interdisciplinary instruction

This research is limited in several ways. First, we were limited to selecting our examples based on those for which we had the most complete information in terms of documentation of students' process and final artifacts, teachers' reflections on their observations of those particular students, and/or post-unit interviews with the students.

This variation in quality and completeness of our data is in part due to contextual variations between participating schools. Indeed, opportunities in arts-integrated data inquiry are shaped by conditions of their implementation (Damşa *et al.*, 2019). The synergies and tensions we observed varied across contexts, which differed in terms of the resources including time, technology access, and incentives or disincentives, that can support cross-domain teaching and learning. For example, the *Dance* school already prioritized interdisciplinary student-led project based learning, had existing routines for teacher collaboration, flexibility in the curriculum for teachers to coordinate across their classes, and traditions for celebrating students' interdisciplinary work in a community-wide exhibition. Meanwhile, the other schools differed in the degree to which teachers were held accountable to standards, and struggled to find time to co-design and coordinate their classes. Support for interdisciplinary instruction also differed between subject areas, with math classes tending to get priority access to laptops, and the arts classes tending to have more flexibility in what content could be covered. Unexpected testing requirements and unreliable technology access interrupted our implementation plans, requiring us to make on-the-fly curriculum adjustments, such as paper-based versions of previously planned digital data visualization activities

As Vess and Linkon (2023) state, interdisciplinary education, while valuable for both teachers and students, often requires significant institutional reform to be effective. The challenges in implementation that we observed echo Power and Handley's (2019) research, which identifies barriers to interdisciplinary instruction to similarly include curriculum inflexibility, regulatory limitations with regard to classroom space and course scheduling, and lack of resources and administrative support. However, Power and Handley also identify facilitators of interdisciplinary instruction, including motivated and qualified instructors, spaces conducive to interdisciplinary collaboration, and institutional goals and individual recognition for interdisciplinary efforts.

Future research might therefore explore ways to create subject-integrated curriculum that is flexible and adaptable to contexts that differ in terms of administrative support, school priorities, and teacher preparation. Future work could additionally explore different approaches to disciplinary integration that may be more or less feasible in different contexts, such as boundary crossing, which the intersection between disciplines is used as a site for transformation, where students can develop new and unexpected ways of doing and thinking (Vereijken et al., 2023). This future work might also explore how to best prepare teachers across subject areas and schools that are differently resourced and supported, to teach arts-integrated data literacy in ways that build on their own and their schools' assets. As Power and Handley (2019) In such efforts, it is important to be mindful of the barriers and facilitators of interdisciplinarity (Power & Handley, 2019).

Generalizability to other arts contexts

Another limitation is our small sample size, which reduces the generalizability of our findings to other teachers and learners. Future research might consider how arts-integrated data literacy instruction might take place in other learning contexts, such as schools with different student demographic and/or achievement profiles, contexts both in and out-of-school; by teachers with different preparation; and in institutions with different disciplinary cultures and resources.

A related limitation is that this study focused on the integration of data literacy into just three arts contexts: visual arts, dance, and English Language Arts. As well, our units largely had students engage with aggregated data and data visualizations, and not with raw data. Future research might test the applicability of our framework to other arts and arts-related learning contexts, such as filmmaking and journalism. Similarly, future work might more systematically explore the potential value of various other curricular approaches to data-art inquiry, such as offering students existing datasets vs. having them generate their own; having them work with raw data vs. aggregated data; and encouraging their creation of artwork based on am inference from data, vs. artwork that concretely maps symbols to individual data points. It is possible that such further research may uncover new data-art practices not captured by this current study.

Conclusion

Drawing on different disciplinary values and practices can promote more humanistic data literacy education. This study has implications for research, design, and practice in the context of interdisciplinary learning more broadly, and in data literacy education more specifically. Given the barriers to cross-subject integration in classroom settings, establishing a robust conceptualization of arts-integrated data literacy learning will guide curriculum designs that build on each discipline's unique affordances to ensure that the learning goals of each are reciprocally supportive (Mejias et al., 2021), and help teachers and researchers to better recognize and support data literacy learning at the intersection of domains.

Differences in the cultures of domains in subject-integrated learning environments can either foreground or background epistemic (mis)alignments. Educators and curriculum designers might support students in navigating the epistemic misalignments between data science and the arts so that these misalignments do not remain tensions that hinder, but might become synergies that support learning opportunities.

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