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ISSUES AND TRENDS

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The trouble with STEAM and why we use it anyway

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Abstract

As an emerging field of theory, research, and practice, STEAM (Science, Technology, Engineering, Arts, and Mathematics) has received attention for its efforts to incorporate the arts into the rubric of STEM (Science, Technology, Engineering, and Mathematics) learning. In particular, many informal educators have embraced it as an inclusive and authentic approach to engaging young people with STEM. Yet, as with many nascent fields, the conceptualization and usage of STEAM is somewhat ambivalent and weakly theorized. On the one hand, STEAM offers significant promise through its focus on multiple ways of knowing and new pathways to equitable learning. On the other hand, it is often deployed in theory, pedagogy, and practice in ambiguous or potentially problematic ways toward varying ends. This paper attempts to disentangle some of the key tensions and contradictions of the STEAM concept as currently operationalized in educational research, policy, and practice. We pay particular attention to the transformative learning potential supported by contexts where STEAM is conceptualized as both pedagogical and mutually instrumental. That is, neither STEM nor arts are privileged over the other, but both are equally in play. We link the possibilities suggested by this approach to emerging theories for understanding how designing for and surfacing epistemic practices linked to the relevant disciplines being integrated into STEAM programs may point the way toward resolving tensions in inter- and transdisciplinary learning approaches.

KEYWORDS

art, epistemic practices, instrumentalism, science, STEAM, STEM, transdisciplinary

1 | INTRODUCTION: AN OFTEN USED, OFTEN DISPUTED TERM

The nascent field of STEAM (Science, Technology, Engineering, Arts, and Mathematics) represents ongoing attempts by educational researchers, practitioners, and policymakers to make sense of and potentially institutionalize the role of the arts in relation to science, technology, engineering, and math learning. Within this evolving field, an enduring tension has been the framing of arts as *serving* rather than *equal to* the various STEM (Science, Technology, Engineering, and Mathematics) fields. While the popularity of STEAM is reflected in its increased usage (e.g., Walmer, 2018), there is considerable definitional divergence regarding what STEAM is: how the term/concept is used, and how useful it is; the contexts under which it is deployed; and importantly, for *whom* and toward *what ends* it is being used (Colucci-Gray et al., 2017, 2019; Conner et al., 2017; Costantino et al., 2015; H. E. Wilson, 2018).

STEAM has been widely generative of new and creative approaches to the fields of the arts and STEM learning, particularly around new media, making, and digital technology (e.g., Colucci-Gray et al., 2017; Conner et al., 2017) in its aspirations to link work *between* (inter-) and *beyond* (trans-) disciplines. Yet, the pedagogy and moniker of STEAM have sometimes been deployed in ways that do not fully consider the epistemological potency or educational potential of deep integration of STEM and the arts (Bartlett & Bos, 2018; Conradty & Bogner, 2018; Hunter-Doniger, 2018). For example, many programs invoke STEAM to emphasize the role of design and esthetics in engineering, scientific modeling, and scientific investigations. Two examples are *Scaling up an innovative STEAM learning environment* at Northwestern University (Stevens, 2017), which focuses on encouraging students' interest in STEM careers; and *One Community, One Challenge: Pop-Up STEAM Studios* (Vasinda et al., 2019), a rural community makerspace project run by Oklahoma State University. Such programs focus on supporting students' STEM learning, including identity development and career aspirations (Scarff, 2015). Many of these programs argue that adding the A to STEM helps to broaden participation in STEM learning (Conner et al., 2017) toward established STEM education goals of expanding corresponding disciplinary literacies and workforces (Atkinson & Mayo, 2010; Land, 2013; Langdon et al., 2011). Other programs seek to explore the emancipatory role that creativity and self-expression through the arts can bring to questions often addressed in the science curriculum such as climate change, conservation, and sustainable development (Aslan et al., 2014; Jennett, Kloetzer, Cox, et al., 2016; Jennett, Kloetzer, Schneider, et al., 2016; Miller-Rushing et al., 2019; Root-Bernstein et al., 2011). These competing motivations and priorities of STEAM reveal a salient tension. On the one hand, STEAM is emphasized as an extension of STEM fields for driving economic and national competitiveness. On the other hand, STEAM has the potential to offer new ways of doing and knowing in the arts and STEM fields, often with emancipatory and critical pedagogical approaches to learning that can be at odds with an economistic focus. In addition, STEAM has quickly advanced toward spaces of funding and programming previously reserved for STEM-related learning due to the increasing U.S. educational policy support alongside popular discourses elevating the role of creativity and innovation in contemporary learning. This can lead to concerns that the STEAM educational frame is a way to secure funding for the arts—and not a genuine coordination of disciplinary ways of knowing across the arts and the STEM fields. As such, if not clearly theorized in ways that can guide practice, shallow representations of STEAM may force a backlash against inter- and transdisciplinary approaches to learning, although many educational leaders are calling to expand such approaches to prepare students for the changing world and workforce (e.g., American Innovation and Competitiveness Act, 2017).

Through a review of the emergent and contemporary iterations of the STEAM concept and moniker, this paper attempts to disentangle key tensions and contradictions of STEAM as currently operationalized in educational research, policy, and practice. Our review of STEAM literature and practices highlights how different instantiations of STEAM vary along two axes of the *pedagogical* and the *instrumental*—where STEAM is positioned as a learning practice of each discipline in the service of the others. We define *instrumentalism* as the application of thought to practical problems (Dewey, 1938) and a rationale for learning (Mellin-Olsen, 1981). We take a particular interest where STEAM is conceptualized as both pedagogical *and* mutually instrumental. That is, STEAM is uniquely positioned in an integrated way (i.e., as epistemic subcultures intentionally coordinated) to mutually promote deep learning in the STEM fields *and* in the arts. Our approach builds on an emerging framework that identifies distinct and overlapping "epistemic practices" of the STEAM disciplines (Bevan et al., 2019) and which ultimately aims to resolve tensions in the relationship between inter- and transdisciplinary learning.

To clarify the conceptual terrain explored in this article, it is important to address terminology usage and what is meant by the distinct deployment of the terms STEAM and STEM. In this paper, we offer critiques of uses of various terminologies (e.g., STEAM or science + art) in cases where the value placed on arts or the STEM fields is unbalanced. Further, we acknowledge that in research and education initiatives, STEM is often used to refer to science alone, leaving out technology, engineering, and math, as well as possibilities for a unique contextualization of each field. In this paper, we recognize STEM as its own unique set of practices that embody but do not overlap exactly with science. Following Knorr-Cetina (2009), we use the term "science" within a poststructural framework to relate to endeavors in both the natural and social sciences and their intersections, noting the surfacing of epistemic cultures across the different and distinct forms of science. We note that the literature has grappled with the problem of conflating science with the other branches of the STEM tree, and also asserted particular identities for STEM that stand within or outside of science. For example, this can be seen in the positioning of science as "above" and of a higher status than technology, engineering, and math (Bencze et al., 2018). Calabrese Barton & Tan (2019) view STEM not as a catch-all term for anything involving science, technology, engineering, or math, but as "the integration of engineering into science learning goals and experiences as outlined by the Next Generation Science Standards" (p. 2). There is also considerable debate about what broadly constitutes "science," with some arguing that social sciences are inextricably bound up with the natural sciences (see work of Rutherford et al., 1994 for the American Association for the Advancement of Science) while others specifically identify areas within STEM such as math as embodying "mathematical sciences" (National Research Council (NRC), 2013). Other studies have shown how specific fields within the STEM designation such as engineering may share epistemic parallels with, but are also distinct from science, technology, and math in their orientations (Cunningham & Kelly, 2017). Our approaches acknowledge the wide field of understandings of science while recognizing in our work how STEM performs multiple epistemic ecologies (Peterson, 2017). While specific organizations and communities use "Science" in a broad and multidisciplinary way—including some we are associated with—for the sake of epistemological clarity, in this paper we have chosen to use the term "STEM fields" in reference to specific educational efforts that might in some instances be called "Science," and in others, perhaps "Technology" or "Engineering."

2 | WITHIN, BETWEEN, AND BEYOND DISCIPLINARY BOUNDARIES

Disciplinary classifications originated in the early 19th century to categorize different fields of seemingly discrete knowledge within the European academy, becoming refined and deepened in the West in the 20th century (Stichweh, 2001). Constructed as such, disciplines have their own tools, epistemic practices, and modes of knowledge production that serve a set of discipline-specific purposes. The construction of academic disciplines has been theorized in terms of its exercise of power in classifying, hierarchizing, and preserving certain forms of knowledge while discarding others (Foucault, 1977; Moran, 2001). Other criticisms of academic disciplines have focused on the inherent problems with creating boundaries to limit the epistemological scope of the study (Fam et al., 2018; Gibbs, 2017; Ingold, 2010). Therefore, boundaries within, between, and across disciplines can be visible but sometimes blurry (Osborne, 2015).

To adequately analyze the boundaries within, between, and across science, STEM, and STEAM, it is necessary to examine the interactions that take place between the disciplines that comprise them. Interdisciplinary interactions between two or more disciplines (Carr et al., 2018) have been conceptualized in different ways: as a search for a more unified or connected form of knowledge that can link different disciplines to make broader claims; as a rebuttal to the existence of disciplines and a challenge to the traditions of knowledge production; and as a means of transcending the limited epistemological potential of existing disciplines on their own (Moran, 2001). For example, an interdisciplinary curriculum may be promoted within education because of its potential to help bring a more historically situated and culturally sensitive approach to teaching math (Zaslavsky, 1993); or for its potential to shape new approaches to ever-stricter regimes of student assessment (Kaufman et al., 2008). Similarly, transdisciplinarity has been defined as a blending of disciplines that places emphasis on co-equal and holistic integration of theoretical and systematic approaches (Choi & Pak, 2006; National Academies of Sciences, Engineering, and Medicine (NASEM), 2018; Osborne, 2015). However, important differences separate conceptualizations of interdisciplinarity and transdisciplinarity. For Peter Galison, interdisciplinarity performs the work of “trading zones” between disciplines, while transdisciplinary approaches bring about new ways of knowing that are enabled by deeper integration of knowledge and methods (Galison & Stump, 1996).

Some have pointed to the need for interdisciplinary and transdisciplinary approaches to solve mounting and complex global, “wicked problems” (Rittel & Webber, 1973), and to improve higher education so that it adequately prepares future generations for a complex ever-globalizing world (Fam et al., 2018; Gibbs, 2017). Other scholars have positioned transdisciplinarity as a way to highlight and link core cognitive skills across disciplines to bolster creativity as an intended pedagogical outcome (Henriksen & Deep-Play Research Group, 2018). In the context of STEAM, the “nexus of practice” (Scollon, 2001) has been a helpful theoretical framework for some to make sense of the integration of practices across boundaries and the ways the intersections of STEM and art practices can give rise to separate and unique outcomes (Peppler & Wohlwend, 2018). This history of study around disciplinary boundaries and interactions shapes the current exploration of STEM and STEAM by illustrating the myriad possibilities for (and problems of) interdisciplinary and transdisciplinary work that can often be left unexamined when attempting to define STEAM. Importantly, prior scholarly work points to the latent power dynamics bound up in transdisciplinary work, reminding us of the critical dimensions of communication and power that frame understandings of transdisciplinary spaces and projects, and prioritization of particular disciplines within such frames (McGarr & Lynch, 2017; Weinstein et al., 2016).

3 | STEM AND STEAM IN THE 21ST CENTURY

An exploration of the STEAM moniker should start with its derivation from STEM—itself a term that has come to have multiple meanings and purposes—and recognition of the work performed and understandings obscured by such acronyms. In the following sections, we briefly examine the history of STEM and STEAM and consider how political power has inscribed certain understandings of the purposes and expectations of the two terms.

3.1 | The origins of STEM

The use of the STEM acronym as an umbrella term to refer to Science, Technology, Engineering, and Mathematics can be traced to the National Science Foundation (NSF) in the United States in the 1990s. With a goal of supporting critical workforce needs, the NSF launched the Education and Human Resources division to address education needs across science, mathematics, engineering, and technology (SMET). Rimes and León de la Barra (2014) stated that this term was later replaced in 2001 with the more "mellifluous" sounding "STEM" (p. 20) but soon thereafter posited as an entity unto itself; whereas SMET had not been so positioned.

Sanders (2008) argued that the STEM term caught the attention of public opinion due to bestselling popular economics books warning that emerging economies like China and India were "outSTEMming" (p. 20) their western counterparts with better math, science, and computer training that would see their economies overtake the United States. As a consequence, "funding began to flow toward all things STEM, and STEMmania set in" leading to the situation where "everyone seems somewhat familiar with the STEM acronym" (Sanders, 2008, p. 20).

Some cautioned about the speed at which the STEM acronym became ubiquitous in education, noting a lack of evidence for grouping the four disciplines of STEM together in the classroom (Zeidler, 2016). As Herschbach (2011) warned:

> *STEM does not represent a specific curriculum model… In fact, it is hard to discern what exactly is meant by "STEM"… Practically any kind of educational intervention that is even remotely associated with science, technology, engineering or math is referred to as a STEM innovation… This lack of a solidifying perception of STEM threatens over the long-term to destroy support for the movement* (p. 98).

The creation of the acronym was perhaps one driver of a move to integrate the four disciplinary areas into one content domain. In 2014, the National Research Council committee on integrated STEM education found evidence that integrating the STEM disciplines could motivate learning. This panel of experts called for an explicit and common language about STEM learning—for example, using the label "integrated STEM learning" to refer to cases where the disciplines were in fact integrated. In other cases, researchers labeled efforts that combined two or more of the disciplines, such as using engineering to advance science learning and identity development, as STEM (Ancheta, 2008; Calabrese Barton & Tan, 2019; NRC, 2009). Others argued that STEM "is not a single subject" (Bybee, 2013). Yet, a recent systematic review of the literature pertaining to STEM education interventions found that there remain multiple, and sometimes inconsistent and ungrounded, ways of conceptualizing STEM education, often foregrounding but sometimes obscuring the integrative nature of work across the four disciplines (Martín-Páez et al., 2019).

As education systems are gatekeepers and agenda setters of the types of "high status" knowledge that schools ultimately teach (Apple, 1978), it is important to consider the political calculus underpinning the formulation and usage of STEM. Although transdisciplinary learning and its political usages in educational policy are not new phenomena (Mansfield et al., 2014; McGarr & Lynch, 2017), the contemporary delineation of a STEM field and its four disciplines as prioritized policy areas influences the wider field of educational policy by hierarchizing disciplines (Weinstein et al., 2016).

Educational policymakers in the United States have explicitly grouped together STEM as critical disciplines required to spur economic and national performance (NRC, 2012) and to maintain global economic power (Weinstein, 2016). STEM is seen to promote transdisciplinary pedagogies to boost economic growth and competitiveness with other countries (Guyotte et al., 2015) and advance the position of the United States in military technology races (for a critique see Vossoughi & Vakil, 2018). In addition, with the rise of STEM as a "field," new tensions have emerged between STEM and science education. Weinstein (2016) argues that the neoliberal "STEMification" of science education substitutes "market value for empirical value" (p. 66), suggesting a potential politicization of the wider field.

Notwithstanding broader sociopolitical tensions and contexts, scholars of science education and STEM education have broadened what gets counted as being part of science and engineering learning to include historically rooted community forms of knowledge and framing everyday and family learning related to the natural world (NRC, 2009). This is an extension of the "everyday cognition" sociopolitical project that centers knowledge-in-use in sociomaterial practice (Rogoff & Lave, 1984). It also relates to the Indigenous resurgence efforts of centering cultural knowledge systems (through stories) as relating to disciplinary ways of knowing (e.g., diverse sense-making, multiple ways of knowing, situated and place-based knowledge; see Abrams et al., 2013; Bang & Medin, 2010; Calabrese Barton & Tan, 2019; McKinley & Gan, 2014). Thus, even within a normative framework of economic competitiveness, STEM has also been conceptualized as a significant equity project promoting cultural heterogeneity through the implementation of epistemic practices (e.g., conceptualizing the building of a deck in the backyard as a math and engineering project).

3.2 | The beginning of STEAM

While initiatives and funding that prioritized STEM continued through the first part of the 21st century, the global financial crisis of 2008 ensured that the arts continued to be deprioritized and defunded, in line with a decades-long trend of marginalizing arts education in U.S. education policy (Bequette & Bequette, 2015). In response to the lack of power that arts pedagogies and/or teachers have in relation to STEM pedagogies and/or teachers, some suggested a proactive approach that required the arts to "sell" themselves to STEM as a form of added value (Wynn & Harris, 2012). Within this context, Rhode Island School of Design (RISD) in 2008 launched a new "low-to-no-cost initiative to justify creativity" (Allina, 2018, p. 77), an initiative that exemplified and shaped what is today commonly thought of as STEAM (STEM and Arts). Echoing the nationalist or economistic arguments for STEM, RISD argued for and sought evidence to support the benefits of integrating arts and design education with STEM as a means to, among other things, help "America to sustain its role as innovator of the world" (Maeda, 2012).

From its inception, policy advocates for STEAM adopted a position of prioritizing the integration of arts into the STEM fields over a more reciprocal positioning between STEM and the arts. Starting in 2011, RISD began to support efforts to introduce STEAM into state and national-level policies and legislation (Allina, 2018). A major achievement of this effort was the creation of a bipartisan U.S. Congressional STEAM Caucus co-chaired by Congresswoman Suzanne Bonamici, a collection of elected federal-level politicians that, as of 2019, included 72 of the 435 members of the House of Representatives. The STEAM Caucus offered a legislative manifesto of sorts for STEAM education, stating that:

> *Advocates for STEAM Education, in the context of advocacy for STEM education, argue that studying STEM subjects alone is not sufficient. Supporters of this concept cite Arts [and Design] as having benefits in mental health, thinking processes, and creativity to validate this assertion* (Allina, *2018*, p. 84).

Building off this political construction of a "STEAM education" and with backing from an emerging grass-roots community of practitioners, Congresswoman Bonamici supported federal legislation in 2015 that called for the integration of the arts *into* STEM subject-programs to promote "access to a well-rounded education" (Every Student Succeeds Act).[1,2] These words demonstrate the political power of STEM as positioning other subjects as integrating *into* STEM, not affording the arts to have a distinct relationship with STEM, but rather as one of an unspecified number of other academic subjects.

[1] The title for section 4107 of The Every Student Succeeds Act of 2015 is *Activities to support well-rounded educational opportunities*. This section addresses that educational agencies (e.g., school districts) are authorized to use their funds, among other ways, to create activities and programs to improve engagement in STEM (including computer science). One of the ways is by "integrating other academic subjects, *including the arts*, *into* STEM subject programs to increase participation in STEM subjects, improve attainment of skills related to STEM subjects, and promote well-rounded education" [emphasis added] (Every Student Succeeds Act, 2015). It is worth noting that while this section (4107) of The Every Student Succeeds Act calls out arts specifically, it leaves the door open for a wide range of other non-STEM academic subjects.

[2] It is our understanding that the National Science Foundation has not ascribed to STEAM to this date as a moniker per any federal policy. As a matter of fact, Congresswoman Bonamici has introduced bill H.R. 3308 to the U.S. House of Representatives back in June 2019 "to amend the American Innovation and Competitiveness Act and the National Science Foundation Act of 2002 [in order] to incorporate art and design into certain STEM education programs." Such a bill has not been passed by the House or the Senate as of September of 2020 (https://www.congress.gov/bill/116th-congress/house-bill/3308).

In contrast to STEM, STEAM is sometimes framed as "widening the tent" by offering to STEM fields a language and a set of practices that foreground the role of creativity in elevating learning across the STEM disciplines (Henriksen, 2014), with less focus on affordances of arts in and of itself. This has shaped the possibilities for the arts as existing, either outside of or within STEM, and not in equal co-construction. This illustrates the discursive and practical subservience often performed by the arts field in appropriating itself to STEM ("adding" an A) so as to become linked with a field bestowed with considerable symbolic and material policy power. It also demonstrates a tendency to situate creativity as being the preserve of the arts domain instead of as also potentially indigenous to the STEM fields.

The political and semantic histories discussed here show how the contours of the STEM and STEAM debates are shaped by the sociopolitical construction of education policy. Implicitly linked to a political positioning of STEAM is recognition of the fundamental imbalance of the arts with its STEM field counterparts, with four distinct and potentially overlapping domains outnumbering the arts and standing in potential conversation with the arts as a singular field. The lack of specificity around how the disciplines interact as part of specific STEAM programs—sometimes including different arts disciplines, or specific STEM disciplines, and potentially integrations of both—is often reflected in the literature, sometimes framed as an "artistic infusion" connecting the disciplines and "motivating for learning" (Henriksen, 2014, p. 4). Through this lens, STEM and STEAM can be conceived as intentionally polysemous phrases used to engage in field-building, suggesting STEAM as a strategy for shifting focus from the arts'perceived marginal status to one of more critical policy importance (Ceccarelli, 2001).

3.3 | STEAM and epistemic practices in arts and science

Recent research and scholarship on STEM and STEAM have begun conceptualizing inter- and transdisciplinary work in these fields in terms of how arts and science specifically share and can uncover epistemic practices (Bevan et al., 2019, 2020; Costantino, 2018). For example, Costantino (2018) advances a mutually engaged transdisciplinary curriculum model-based around creative inquiry, a process that iterates problem definition, multimodal inquiry, problem refinement, in-process critique, inquiry, design, refinement, and exhibition. In this model, the focus is squarely on epistemic practices across arts and science, including exploration, meaning-making, and critiquing. Costantino suggests that such an approach creates a "third space" generating hybrid content and epistemology for arts and engineering (Costantino, 2018, p. 105).

The epistemic framework for STEAM (see Table 1; Bevan et al., 2019) we are exploring is in the context of transdisciplinary arts and science integrated into out-of-school programs for young people. This framework draws on the scientific practices explained in the K-12 Framework for Science Education (NRC, 2012) and Kafai and Peppler's (2011) arts framework. A question arises whether the practices engaged in such programs are distinct to STEM or to the arts and whether they additionally take on new hybrid forms, as we conjecture in the center column of Table 1. The framework articulated below was collectively assembled by the writing team and involved ongoing discussions of collective and individual STEM and arts-based research projects, which resulted in the iteration of hybrid epistemic practices (Bevan et al., 2019, 2020).

For example, the scientific practice of modeling as a mechanism for the conceptual or empirical representation and understanding of phenomena (e.g., Svoboda & Passmore, 2013) may have value in an urban youth program focused on the planning of building community gardens in the context of gentrification. Artists as agents for change may start creating models and representations valuable to the same program in marshaling community support for the project through murals, posters, and flyers depicting the vision and plans (e.g., Ley, 2003). This same program may go back and forth between such practices.

Another aspect we are exploring is whether such programs also develop hybrid forms of practice that are particular to transdisciplinary STEAM programs such as argumentation. For instance, scientific knowledge has been constructed over time through processes of evidence-based argumentation (via peer review). This epistemic

TABLE 1 Epistemic practices in STEAM (Bevan et al., 2019)

	STEM practices	Conjectured STEAM practices	Arts practices
Exploring	Asking questions/defining problems	Noticing and questioning	Deep noticing
	Planning and carrying out investigations	Exploring materiality	Deconstructing component elements and their respective meanings
	Using mathematical and computational thinking	Defining the problem space	
Meaning-making	Developing and using models	Producing tentative representations	Applying artistic principles to augment meaning
	Analyzing and interpreting data	Conducting principled iterations/revisions	Designing interrelations within and across multiple sign systems
	Constructing explanations/designing solutions	Engaging multiple modalities	Referencing or combining existing works and ideas
		Finding relevance	
Critiquing	Arguing from evidence/peer review	Critical historicity; hacking the ideas of others	Critical historicity; negotiating what constitutes a "good" project
	Evaluating and communicating findings	Cultivating dissent	Given a particular artistic goal, evaluating how successfully this goal has been met
		Holding commitments to standards of the field	
		Sharing results/"Audiencing"	

Abbreviations: STEAM, Science, Technology, Engineering, Arts, and Mathematics; STEM, Science, Technology, Engineering, and Mathematics.

practice has been spotlighted in current science education improvement efforts in the United States, based on studies that show that students typically have limited experience with constructing and considering evidence-based explanations for the phenomena they investigate (e.g., D. Kuhn, 1993; McNeill et al., 2006; Newton et al., 1999). Although less grounded in notions of evidence-based argument, art practices and knowledge have similarly been constructed in a dialogue (or argument) between the past and the present, with new forms emerging in response to antecedents. Further, arts-based practices are more explicitly developed in relationship to historical social moments; this relationship to historical moments may be less explicit in science-based practices, though they are no less present (T. S. Kuhn, 1962).

We suggest that STEAM programs may often emphasize a hybrid of these two epistemic practices, which we could call "hacking," that is, the deliberate appropriation and repurposing of existing tools and knowledge. Examples of hacking include activities taking place in physical spaces designed to support resistance and countercultures (Grenzfurthner & Schneider, n.d.) or using Twitter hashtags to start social movements (Santo, 2011). Other endeavors that could be understood as hacking include Black youth using community-created dances to narrate and position their identities and experiences around science (Chappell & Varelas, 2020), and youth and educators connecting public science displays to political statements and identities (Shea & Sandoval, 2020). This hacking practice would be recognized in the bottom row of Table 1 (above) as a type of "critiquing" practice that exists between the STEM fields and the arts, leveraging epistemic practices from each field in a new hybrid form. Scientists and artists engage in hacking all of the time, as do chefs and fashion designers. Our conjecture is that STEAM programs may be more likely than STEM programs to emphasize this practice in different ways. In doing so, under the guise of “hacking,” STEAM programs may make the oftentimes invisible or underdeveloped scientific practice of evidence-based argumentation more visible and central to learners. They may also make more visible the centrality of disciplinary dialogue inherent to the arts.

Our epistemic framework highlights the potential for STEAM to more fully acknowledge and leverage its inter- and transdisciplinarity, to create new ways of learning about and researching arts and STEM field collaborations. It also demonstrates the need for a more coherent understanding of when and how STEAM, as iterated in pedagogy, research, and practice, encourages or restricts productive epistemic connections.

4 | RESEARCH AND PRACTICE ACROSS STEAM CONTEXTS

In this section, for the purposes of understanding STEAM as an educational practice, we explore different approaches where research and practice have positioned the arts in relationship to the STEM fields along two axes: *instrumental* and *pedagogical* power. In the instrumental axis, we explore one-sided and mutually instrumental approaches together with pedagogical and nonpedagogical dimensions (see Figure 1). Examining these positionings of arts and the STEM fields can potentially point to a more cohesive understanding of the tensions and boundaries regarding STEAM.

4.1 | Theorizing instrumentalism and pedagogy as rhetorics of STEAM

Mindful of the wide interpretation and even sometimes arbitrary nature of the STEAM concept, we propose four approaches or *rhetorics*, what Sutton-Smith colorfully called the “intellectual odor” or “implicit narrative…to persuade us that [a] choice and direction of research or study is sound [or satisfactory]” (Sutton-Smith, 1997, p. 8). Rhetorics (see Figure 2) are persuasive discourses that explicitly or implicitly position a particular method or embodiment as worthy of representing or defining the field. Framing this typology of approaches to STEAM as rhetorics may help illuminate how each perspective on STEAM can influence or imbalance the discursive field, offering a sense of what type of dynamics currently shape how we come to understand STEAM. Within each of these rhetorics, we consider how the structure, tensions, and epistemics of engagement with both arts and the STEM fields may comprise a particular form of STEAM.

For the purposes of our analysis, we also set out to clarify the assumptions and tensions regarding instrumental approaches. We follow the work of John Dewey (1938), who conceptualized *instrumentalism* as the application of thought to practical problems, and Mellin-Olsen (1981) who defines instrumentalism in education as primarily a rationale for learning. We expand the definition of instrumentalism in STEAM practices as having the potential to operate on three levels: *intent* or motivation of the practice, the *nature of collaboration* between the arts and the STEM field, and the *outcomes* or perceived outputs of such practice.

For instance, the intent or motivation of a *one-sided instrumental* approach to arts and the STEM fields is primarily (but not exclusively) concerned with operationalizing one discipline to serve another, thus implicitly

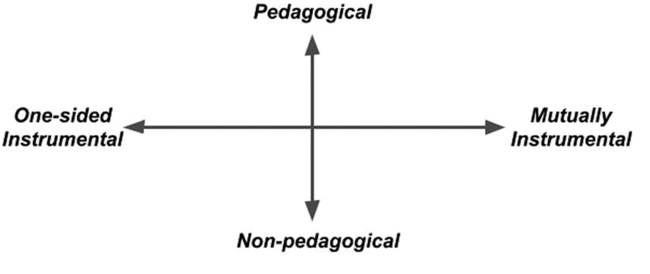

FIGURE 1 Instrumental and pedagogical approaches

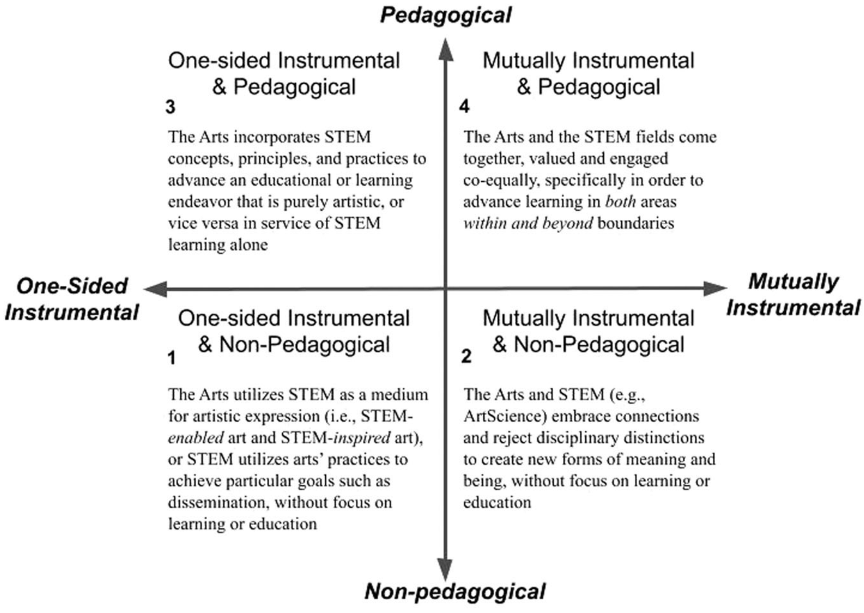

FIGURE 2 Instrumental and pedagogical rhetorics of STEAM. STEAM, Science, Technology, Engineering, Arts, and Mathematics; STEM, Science, Technology, Engineering, and Mathematics

positioning one discipline above others. This stance would hold that particular disciplines may be directionally leveraged to support other disciplines that may lack particular features (serving to motivate instrumental practices). The nature of collaboration of one-sided instrumentalism in transdisciplinary exchanges engages one or more disciplines but in a superficial manner. The outcome or output from a STEAM project shaped by instrumental practices would reflect a superficial engagement of one or more disciplines, that is, it may only consider, enhance, or change one discipline while ignoring another.

In contrast, a *mutually instrumental* approach has several characteristics that define its stance toward the different disciplines within STEAM. Fundamentally, a mutually instrumental approach frames all disciplines as equal and in dialogic conversation, making the motivation for STEAM one based on transdisciplinarity. This is not to suggest that a unidirectional instrumental approach is not capable of generating new ways of understanding and practicing integrated disciplines. Nor do we mean to downplay the power of STEAM applied to larger, practical purposes—for example, preparing young people for future opportunities or in service of social justice. Rather, it is to suggest that, in prioritizing a one-sided instrumental approach, a type of disciplinary use is articulated not explicitly calling out dimensions of disciplinary balance as a starting point.

Considerable efforts within academic literature have sketched *pedagogical* and/or conceptual models for how integrative arts and STEM fields can transcend tendencies toward one-sided instrumentalism. Yakman's (2008) ST∑@M model accentuates the integrative nature of the disciplines and defines STEAM as "Science and Technology, interpreted through Engineering and the Arts, all based in a language of Mathematics" (p.18). This selectivity of which disciplines perform interpretive work and which provide discursive or language foundations has been criticized for closing off possibilities for inquiry across disciplines (Quigley et al., 2017) and not encouraging a deeper or more systematic understanding of how each discipline interacts with the others. In contrast, Quigley et al. (2017) outline a conceptual model for STEAM teaching based around the notion of transdisciplinary inquiry across instructional *content* and learning *context*. The content comprises problem-based delivery, discipline integration, and problem-solving skills, while the learning context includes instructional approaches, assessment practices, and equitable participation learning strategies. Through its focus on problem-based delivery and problem-solving skills, this approach begins to consider and articulate how epistemologies are shared and expressed within and across disciplines.

Our focus on analyzing STEAM in terms of pedagogy is based on the term's origination in the domain of educational research and practice. Yet practitioners of arts and STEM collaborations sometimes use STEAM to attract interest in their projects or align with similar communities of practice, blurring the lines of how STEAM might be seen as a distinct field of pedagogy. Our aim in analyzing the prevalence of pedagogical perspectives in different forms of STEAM is to identify the explicit invocation and usage of inter- and transdisciplinary approaches as a way of advancing education and learning. It is beyond our scope to consider the various types of pedagogies appearing in STEAM practices (either seen or identified as such), while arts and STEM field practices provide clear opportunities for learning that could constitute informal pedagogy. As with our conceptualization of how instrumental approaches might shape definitions of STEAM, we have chosen to focus as well on the instances of STEAM where there is a clear pedagogical *intent*, *collaboration*, *and outcome*.

STEAM as a primarily *pedagogical* framework often includes explicit educational frames or practices where one discipline or set of disciplines is seen as being core to the learning experience or is identified as the primary/only subject (intent) and "uses" another discipline (nature of collaboration) to achieve its goals (outcome). However, many practices of STEAM are *nonpedagogical*, that is, they are present in popular culture, the contemporary arts, or in the STEM fields. In these instances of STEAM, it is possible to observe distinct strategies of using the arts to serve the goals of the STEM fields and vice versa. We include such approaches here for two reasons: first, because some discussions of STEAM fail to distinguish primarily STEM or artistic practices from educational practices; second, because the ways in which arts and STEM are integrated into professional activity or popular culture may shed light on questions of education and pedagogy.

In the section that follows, we describe in detail the proposed four rhetorics of STEAM, examining, in particular, the pedagogical and instrumental intentions, nature of collaboration, and outcomes that underpin each approach.

4.2 | One-sided instrumental and nonpedagogical (Figure 2, Quadrant 1)

In this STEAM rhetoric (see Figure 2, Quadrant 1), STEM fields can act as a set of materials (i.e., technologies, phenomena) that serve as the medium for the arts and artistic expression (Peppler & Wohlwend, 2018). This approach recognizes the potential benefits of instrumentalizing the STEM fields for arts, rather than the reverse, as has characterized many STEAM approaches since the 1990s (McCarthy et al., 2004). Creative instrumentalism of STEM can occur through STEM-*inspired* art, such as paintings about scientific subjects, or dance as an interpretation of planetary motion (e.g., Wellcome Trust's SciArt schemes; see Glinkowski & Bamford, 2009).

This process also manifests through what might be called STEM-*enabled* art, where engagement with explicit STEM practices facilitates the creation of artistic work. One type of this artistic practice is "bio-art," which refers to the experimental use of biotechnological processes to create conceptual and material artworks (Kac, 2007). Examples of bio-art include applying different technologies to the human body (e.g., Cypriot-Australian artist Stelarc who used his own body as a "surface" for his art; http://stelarc.org/?catID=20290), or editing the genomes of genetically modified organisms to revert them back to their "wild-type status" (Portuguese artist Marta de Menezes' 2018 exhibit "Truly Natural"; https://martademenezes.com/portfolio/truly-natural/). Bio art, as a subfield, shows how functional use of STEM fields can serve artistic ends, even gaining legitimacy within academic institutions (e.g., scientific and artistic coinquiry is conducted at SymbioticA—The Centre for Excellence in Biological Arts in the School of Anatomy & Human Biology at the University of Western Australia).

Instrumentalizing disciplines this way evinces a form of STEAM with certain tensions. For example, there is the potential that the core values of science may not necessarily be accurately depicted or respected during the artistic process, or that transdisciplinary collaborations may be one-sided. Used this way, the arts can reinterpret, modify, or even abuse STEM practices without necessarily affecting the art. Conversely, deploying science and STEM as a signifier—even when transdisciplinarity is the intention—may both serve an instrumentalizing purpose and potentially diminish the perceived value of the artistic practice. This can be observed in the example of artist Ryoji Ikeda's "CERN[3]-inspired" installation *Supersymmetry* (http://ryojiikeda.com/project/supersymmetry/), in which the artistic rendering of the CERN experience was critiqued as an "array of beeps, whooshes, dazzling strobes, and light pulses…signifying nothing" (Jones, 2015).

The field of citizen science (Irwin, 2002) also exemplifies this rhetoric. Citizen-led projects are often valued for their reliance on crowd-sourced human creativity or pattern-spotting that can, for example, overcome the limitations of computer algorithms (see Dobreva & Azzopardi, 2014; Jennett, Kloetzer, Cox, et al., 2016; Jennett, Kloetzer, Schneider, et al., 2016). Here, the practice of art is more explicitly focused on how creative and artistic practices such as artwork, creative writing, gamification, and idea/model iteration might be used to serve scientific goals (Jennett, Kloetzer, Cox, et al., 2016; Jennett, Kloetzer, Schneider, et al., 2016). For example, the *Galaxy Zoo* digital platform uses gamification, game design, and computer art design to create an astronomical classification citizen science project (https://www.zooniverse.org). A separate recent study of avian and insect interactions created both an online game for citizen scientists to classify model–mimic pairs, and a separate virtual reality game to simulate model–mimic–predator interactions that allowed 45 humans to "play" the role of bird predators (Miller-Rushing et al., 2019). For citizen science projects, such creative practices may however be a byproduct or a communication strategy rather than an intended artistic practice, so a tension surfaces regarding how and when we can see certain artistic practices as being implicit or explicit to arts and science collaborations.

As an instrumental tool, the arts can support scientific and STEM research by providing a new set of tools (e.g., visual aids) to advance research agendas (e.g., Miller, 2014), for example through visualizing high-resolution numerical simulations of statistical systems like fluid flow, galaxy systems, or animal flocking in which significant patterns become discernible only through visual human detection. Following the frequently articulated logic of using creativity to foster innovation (Segarra et al., 2018), other fields of science have looked to how the arts can extend or deepen practice in the STEM fields. For example, the arts and creativity have been used to justify a need to develop new strategies in conservation science to sustain the biodiversity of the planet, through approaches that foster "creative" solutions to mounting conversation problems (Aslan et al., 2014). Although a seemingly straightforward and unproblematic usage of arts for STEM, there is a possibility for misalignment between the intent of the STEM practitioner and the goals for the art being used, or for art to be interpreted or understood in a limited, even nonartistic sense.

Looking across a range of one-sided instrumental approaches that do not aspire to be pedagogical, this rhetoric of STEAM largely eschews meaningful exploration of transdisciplinarity. Instead, it advances particular repertoires of either unidirectional instrumentalism (e.g., art "using" technology or vice versa) or of the use of one discipline to expand or extend work in another. While this latter form can be productive, it still restricts transdisciplinary possibilities of the emergent STEAM field. Despite such superficiality, these practices often appear to embody authentic forms of arts and STEM collaboration. This rhetoric positions STEAM as something of a signposting exercise where the interplay of arts and the STEM fields is easily spotted, but neither mutually nor meaningfully engaged. This rhetorical construction of STEAM suggests a limited or unintentional interfacing with the conjectured epistemic STEAM practices (identified in Table 1 above) where its conceptualization and practice do not place emphasis on exploring transdisciplinarity.

4.3 | Mutually instrumental and nonpedagogical (Figure 2, Quadrant 2)

In this approach, the instrumentalization of the arts for STEM or vice versa is *mutually instrumentalized* (see Figure 2, Quadrant 2) making explicit the collaborative, transdisciplinary nature of arts and STEM work, and are

[3]European Council for Nuclear Research (Conseil Européen pour la Recherche Nucléaire).

embodied by such approaches and outcomes. Proponents have hailed the potential for STEAM or arts and STEM integrations to generate new epistemologies, such as "ArtScience," which combines elements of scientific exploration, design, engineering, and art in one space (Root-Bernstein et al., 2011). The ArtScience movement is concerned with embracing connections and rejecting disciplinary distinctions, using the transdisciplinary elements of invention and exploration as a bridge for arts and science to create entirely new forms of meaning and being. Under this conceptualization, STEAM becomes a means of disabusing or unsettling disciplinary romanticism of arts and STEM. It also can potentially aid in recognizing powered dimensions and commodified forms of academic disciplines.

Some art practices generate new artistic and STEM modalities that rely on transdisciplinary work to build new ways of knowing and being in both disciplines. Many other artists, reflecting on preoccupations, anxieties, and questions in modern society use STEM as both medium and message. For example, Hito Steyerl's installation *This Is the Future* in 2019 uses multiple large-scale video screens to imagine an artificial intelligence to come. The "lush animations" (Madoff, 2019) that she produces move backward and forward in time, confounded by sudden, violent, and chaotic shifts in movement and image that suggest not an ordered techno-universe but a more primordial and earthly state. Ryoji Ikeda's 2019 *Dataverse*, a massive video representation of data streams and medical imagery, compels the viewer to consider how much of the human experience exists, alongside our embodied experiences, in a data-driven universe. In these cases, without pedagogical purpose, artists find the intersections of science, art, and social life as a place to ponder and to imagine. Art is not promoting science, and science is not promoting art. Instead, together they offer views into contemporary life. This rhetoric can potentially uncover and emphasize conjectured epistemic practices of STEAM (see Table 1) that include aspects of exploring (e.g., noticing and questioning, defining the problem space) and meaning-making (such as engaging multiple modalities, or finding relevance) as *primarily* transdisciplinary pursuits.

Other fields in which it is possible to observe the integration of the STEM fields and arts as generating new epistemologies is in the broad field of digital arts, in which major advancements have been seen in the world of popular culture and entertainment. Pixar Animation Studios is a notable example of how the arts and technology can be both generative and paradigm-shifting. Pixar's scientists and artists are at the forefront of both arts and technology and lead the field of computer graphics, evidenced not only by their commercial success but through their participation in major international computer graphics conferences such as SIGGRAPH (see e.g., https://sa2018.siggraph.org/en/). Importantly, Pixar's leadership has explicitly framed their approach to combining arts and technology as a problem-solving process, suggesting a focus on how epistemic understandings are formed through and across disciplines (Catmull, 2008). While such work does at times rely on operationalizing technology for arts and vice versa, the intentions of the work are not to use arts to make STEM, or STEM to make art. The process is explicitly focused on the transdisciplinary work and the outcomes can be recognized as art, STEM, and something entirely new in the fields of technology and digital arts (S. Wilson, 2002).

In contrast to one-sided instrumental approaches without a pedagogical focus, this rhetoric of STEAM embraces transdisciplinarity as the foundational motivation and process underpinning STEM and arts collaboration and seeks to produce new forms and meanings from the collaborative process. Although there is not an explicit pedagogical focus in such work, the generative nature of balanced transdisciplinary collaboration can lend itself to learning outcomes because of the new epistemologies enabled by such practices (e.g., the popularity of Theo Jansen's Strandbeest art project, discussed in the following section, leading to its marketing and dissemination as an educational activity).

4.4 | One-sided instrumental and pedagogical (Figure 2, Quadrant 3)

Perhaps most common in educational contexts is the one-sided instrumental pedagogical approach to STEAM (see Figure 2, Quadrant 3). In these cases, STEM is incorporated into arts programs, or the arts are incorporated into

STEM programs, whether in formal or informal settings. In the first instance, a clear example is in the designation of STEAM as part of the arts curriculum in K-12 education (Yakman & Lee, 2012), which affords the development of new STEM-referent methods of teaching and learning the arts. The challenge of an uncritical policy inclusion such as this is that an unguided implementation may be superficial or poor and not take advantage of the epistemic connections across arts and the STEM fields (Connor et al., 2014). In the second instance, the positioning of arts as a tool for STEM is a commonly found rhetorical position within the growing body of STEAM literature (Bequette & Bequette, 2015; Conner et al., 2017; Land, 2013), and in the burgeoning Maker field (Taylor, 2016). A common refrain for the inclusion of art practices or pedagogies in STEM or science learning is that the arts provide a creative or “innovative” aspect missing from science pedagogies (Segarra et al., 2018). For example, this could include using field drawings, visualizations of field lines in Maxwell-Faraday's representations of electromagnetic fields, or the imagining of dinosaurs from fossil remains, as a way to introduce the subject.

Outside of formal education, the arts can also be instrumentalized for pedagogical purposes for science communicators by assisting in the development of teaching tools or communication approaches that enhance learning for learning's sake; what the National Academies of Sciences, Engineering, and Medicine (NASEM) calls the cultural rationale for science literacy (NASEM, 2016). In such cases, the STEAM concept is largely predicated around the rhetorical notion of “addition,” bringing the arts into conversation with STEM in a way that generates additional or mutual benefits beyond STEM or science learning outcomes, but that still recognizes the primacy of STEM in setting the educational policy or science communication agenda.

From the research perspective of the STEM fields, the arts and artists can also serve as useful platforms or partners to satisfy public engagement or demonstrate impact criteria for research funding, by framing such efforts as “communication, engagement and collaboration through art” (Sleigh & Craske, 2017, p. 326). The benefits of this type of integrated practice involve the facilitation of potentially more accessible ways into STEM for public audiences. Practices of the STEM fields also frequently rely on using artistic representations of scientific concepts to clarify and present their work to the public as part of a STEM literacy building agenda. In this context, arts can advance STEM literacy, which in turn is in service of what NASEM calls the economic, personal, or democratic rationales for science literacy (National Academies of Sciences Engineering and Medicine, 2016). The field of *SciArt* is perceived by artists to fit into this category but has been deemed in some ways to be lesser art, in recognition of tensions between its transdisciplinary intent and material outcomes (Sleigh & Craske, 2017). SciArt has been characterized as an approach to science communication that merges arts and science practices through a focus on creativity (Sleigh & Craske, 2017). However, some describe tensions regarding how arts serve scientific ends as manifesting through the superficial quality of art under such contexts, with art becoming mainly illustrative and literal, which would not necessarily invite new questions or new ways of thinking about arts in relation to science (Sochacka et al., 2013).

One-sided instrumental approaches to STEAM may also move beyond purely artistic or scientific endeavor to take on pedagogical attributes, displaying potential for types of STEAM to evolve or move between quadrants. One example is the transformative work of the Dutch artist Theo Jansen. Jansen refers to his Strandbeest wind-powered skeletons—massive sculptures that float across beaches and are capable of storing and transferring energy—as the creation of “new forms of life.” With Jansen's work, which upon the first appearance instrumentalizes scientific tools to make art, the fusion between physics, design, arts, making and engineering generates a new materiality that embodies both arts and STEM. The artifacts are ingeniously designed to use the kinetic energy of wind to move large, mechanical objects. Beginning as primarily an artistic work, the Strandbeest project has expanded into the Maker community through Jansen's Mini Strandbeest Kit, adding a pedagogical dimension for shaping understandings of how engineering and arts can be productively combined.

In general, this STEAM rhetoric relates to our conjectured epistemic practices (Table 1) largely through an absence of engagement around transdisciplinary possibilities. However, the instrumental benefits of the arts (in a broader sense than just science) are wide and varied. They promote positive individual and societal outcomes in cognitive, attitudinal and behavioral, health, social and economic spheres (McCarthy et al., 2004). Within science education practices where the arts are instrumentalized, these aspects are perhaps less explicitly articulated, signaling ways in which opportunities to recognize and promote epistemic connections across the disciplines may go unheeded.

4.5 | Mutually instrumental and pedagogical (Figure 2, Quadrant 4)

The final rhetoric of STEAM we identify (see Figure 2, Quadrant 4) seeks to combine arts and the STEM fields as valued and engaged coequally, to advance learning within, across, and beyond field boundaries. Ideally, spaces that align with this rhetoric avoid placing one discipline above another in terms of importance or time, but strive to either advance multiple disciplines simultaneously or forge new transdisciplinary space at the intersection. Such forms share a number of similarities: an explicit recognition of the equal standing and mutually beneficial contributions of both arts and the STEM fields; a desire to integrate disciplines as a way of growing interest and learning potential in both; and an interest in positioning transdisciplinarity as a means to generate and expand greater potential for deeper learning in both (e.g., Liao, 2016; Marshall, 2015).

While such approaches can be found in schools and colleges (National Academies of Sciences Engineering and Medicine, 2018), they are not limited to formal education contexts, and increasingly some of the most innovative approaches being implemented are in out-of-school or informal contexts, and even in nonpedagogical spaces (such as festivals, other entertainment or cultural venues, or even bars and nightclubs). Within this rhetoric are practitioners and practices that may or may not self-identify as STEAM, despite displaying clear characteristics of transdisciplinary work connecting arts and STEM.

Recent research projects by the authors have attempted to shed light on the opportunities and tensions of mutually instrumentalized, pedagogical approaches to arts and STEM field collaborations occurring primarily in out-of-school contexts. We highlight several examples here and describe how such practices can at times both embody (and potentially even obscure or reject) affiliation with STEAM. For example, Guerilla Science in New York City, USA, and London, England, aims to "revolutionize how people connect with science through transformative experiences," and create artistic and theatrical performances and events that are most often staged as part of music festivals or other cultural events (such as at county fairs, or at other cultural happenings such as Burning Man or Glastonbury Festival; Bevan et al., 2020; Rosin et al., 2019). Guerilla Science's "science by stealth" approach directly creates opportunities for learning about science through arts in spaces where there are limited expectations for learning (Bevan et al., 2020; Bultitude & Sardo, 2012; O'Connell et al., 2020). The unique elements of their approach for facilitating learning—relative to many other designed Informal Science Learning activities—center on generating excitement, providing opportunities to explore the nature of science, and helping build audiences' identities as science learners (NRC, 2009). One well-developed project, since 2010 Guerilla Science has run the *Intergalactic Travel Bureau*, an interactive theatrical experience exploring the incredible possibilities of space tourism. Complete with themed décor and retrofuturistic artwork, this is a travel agency with a cosmic twist, where guests plan their next trip to the stars (think the two TV shows *Jetsons* meets *Mad Men*, with a dash of the two space companies *Virgin Galactic* and *SpaceX*). Costumed actors invite guests to step inside for a personal consultation with role-playing actors and space scientist "agents." The content, dialogue, and narrative are based on cutting edge space-science research, that has often been carried out by the space science researchers themselves, who help to customize the experience using their own research. For example, conversations explore the physical characteristics of each planetary destination and its physiological suitability for the guest in terms of journey time, habitability, and atmospheric composition, so as to identify the best holiday for them. Guests discover unmissable highlights on the Moon, Mars, and Europa, picking up elements of planetary science, geology, and more along the way, and considering the effects of microgravity on the human body and mind. Consultations in the bureau use humor and narrative touching on the wider social and political contexts and motivations for humanity's desire to go into space. In this practice, the arts—realized through narrative, theater, carnival, and play (Bevan et al., 2020)—are not merely a hook or attraction to promote science learning, but a fundamental part of the pedagogical experience, where engagement in the arts and science together results in new understandings of both fields.

Science Gallery at Trinity College Dublin offers another example of a mutually instrumentalized pedagogical STEAM approach. Since its establishment in 2008 (Gorman, 2008) at least three thematic exhibitions have been developed each year. These exhibitions combine arts and science to engage visitors in conversations around the challenges facing society (Brunswick, 2017). Exhibition topics have included "INTIMACY," "STRANGE WEATHER," and "HUMANS NEED NOT APPLY" and are accompanied by a program of events and educational activities. Inspired by the artworks, critical discourse related to the theme is instigated with visitors to the gallery space by Science Gallery Dublin's mediator team, a group of young people who share a passion for communicating arts and science (Enros & Bandelli, 2018). Additionally, the flagship education program called OPEN MIND Studio, consists of 5-day intensive courses for 15- to 16-year-olds that are facilitated within Science Gallery Dublin's spaces. This age group has traditionally low engagement with cultural institutions, especially for young people living in socio-economically disadvantaged areas. OPEN MIND Studio offers the opportunity for young people to immerse themselves in STEAM activities outside a classroom setting—one such example is a tinkering workshop in which participants learn to create circuits and use microprocessors to control LEDs and other components. They use these circuits along with traditional paper crafts to illuminate a small diorama. Students must each build their diorama to tell one line of a story, chosen from the tradition of Irish folklore and mythology. This activity incorporates elements that are often present in formal science and engineering curricula, as well as dimensions of informal science learning including opportunities to generate interest in physical phenomena, to participate in learning practices with others, and to build science identity (NRC, 2009).

An example of how both the STEM fields and arts can be equally in play is when an art exhibition in the gallery space is also used to collect or refine data to help generate new scientific results for publication. *SocioPatterns* was an experiential exhibit as part of the INFECTIOUS: STAY AWAY exhibition in Science Gallery Dublin in 2009. Visitors wore electronic badges as they moved through the exhibition space, and a sensing platform detected close-range proximity among individuals. This data was used to generate high-resolution visualizations of a virtual epidemic (van den Broeck et al., 2012). Science Gallery Dublin also brings this mutually instrumentalized pedagogical STEAM approach to its programming of events outside of the gallery space such as science shows and festivals (Roche, Cullen, et al., 2016; Roche, Stanley, et al., 2016) and through its participation in research projects and international networks (Roche et al., 2018). This STEAM approach ensures that anyone who takes part in events, activities, or exhibitions at Science Gallery Dublin are invited "to explore broad topics through the lens of art and science in ways that can be witty, clever, even subversive, but never traditional" (Hurley, 2019, p. 34).

Other efforts have pioneered transdisciplinary approaches to equity through the integration of STEM, arts, and justice-driven community engagement. For example, YR Media in Oakland, California is a national network for next-generation news and arts where young people whose stories are under- and misrepresented in public dialogue produce media that unlocks opportunities for makers, and shifts national conversations on the pressing social issues of our times. In 2010, a team within YR Media established a division of the newsroom where, together with professional designers and developers, young people combine journalism, design, data, and computer science. Products of the Interactive team reach audiences via YR Media's independent platform, legacy media partners including National Public Radio (NPR), mobile networks including Apple's App and Google's Play stores, and social media channels through which young people engage their peers, advocates, thought-leaders, and policy-makers. In 2019, the Interactive team partnered with MIT App Inventor to launch a 3-year initiative that takes an ethics- and equity-based approach to "outsmarting" artificial intelligence (AI). Among the broad array of critical literacy and media production projects backed by this initiative is the web-based interactive, *Erase Your Face*, a critical exploration of facial recognition software, a technology that is increasingly omnipresent in both physical and digital spaces.

Erase Your Face is playful and dead-serious. To create it, young people first had to immerse themselves in concepts, debates, and models related to AI, exploring how facial recognition works and problems with its deployment in diverse contexts ranging from law enforcement to concert arenas. The team then designed a web-based interactive that invites users to experiment with various ways to dodge facial recognition by dragging and dropping filters, accessories, fashion, and make-up styles over a face of their choosing. Importantly, the young people imagined, designed, and coded every aspect of the interactive. They exercised critical computational literacy (e.g., Lee, 2017) required to understand the implications of their own choices—for example, if they invite users to upload photos of their own faces into the interactive, do they risk contributing to the very problems related to surveillance and personal data "leaking" the project aims to critique?

Erase Your Face producers also interrogated their design decisions to optimize an intuitive user experience that is both visually compelling and aligned with their peers' digital esthetic sensibilities. At one point in the making of the project, the young people played with analog versions of what the app does digitally, affixing colorful masking tape, construction paper cut-outs, and sparkly stickers to their actual faces. They posed for selfies and then ran those files through Amazon Rekognition software to test detectability. Throughout the process, they reflect critically on artificial intelligence as a way of knowing—its delights, affordances, limits, and potential for causing harm. Through the widespread distribution of *Erase Your Face*, the goal of the project is to diversify and broaden participation in these same types of crucial critical reflections at the intersection of technology, arts, and equity.

Perhaps most importantly, this rhetoric offers the potential to connect mutually instrumental, deeply trans-disciplinary practices with learning outcomes, enabling a form of STEAM that is primarily interested in exploring disciplinary connection and integration, for the purpose of eliciting a more pedagogically rich process and outcome. This rhetoric encourages dispositions that link, rather than silo, epistemic practices that cut across the different disciplines of STEAM, and which can potentially lead to social outcomes that transcend building individual knowledge about arts and the STEM fields. This linkage is made richer through a focus on what different disciplines share and can achieve through collaboration, and how they complement or support each other. Therefore, we find that it is the most favorable approach for generating and embedding meaningful epistemic practices in STEAM, and encourages the kinds of "hacking" behaviors and thinking that mutually repurpose arts and STEM learning in service of deeper learning outcomes (see Table 1).

At the heart of these STEAM and equity approaches, sometimes explicitly and sometimes not, lies a "practice turn" that positions learning activities as engaging in the epistemic practices of the disciplines toward achieving specific, localized transdisciplinary purposes—such as engaging in investigations to better understand community disparities not as a matter of science alone but also as a socioeconomic, historical, and political matter requiring action. This vision of STEAM is anchored in social purpose and meaning-making, using disciplinary practices as the means for addressing questions and advancing agency. Our work developing an epistemic framework for arts and STEM would therefore envision STEAM as a practice that must be foundationally transdisciplinary and potentially generative of meaningful social change.

5 | CONCLUSION

In this paper, we have critically analyzed the concept of STEAM, with a broader aim of seeking to understand what STEAM is and what it can be. Having developed as a nascent field of (somewhat) arbitrarily paired disciplines, largely in response to the emergence and subsequent educational policy power of STEM, current manifestations of STEAM comprise many forms and are often theorized and defined in divergent and sometimes contrasting directions. Among recent calls to return to humanities and to integrate arts and humanities into STEM (NASEM, 2018), it is necessary to consider what is possible with transformative STEAM approaches as they increasingly become framed as contributing to improved educational outcomes. Articulating a typology of STEAM rhetorics offers a means to clarify and further probe the transformative potential of STEAM, in light of its contemporary usages and aspirations. By proposing this typology across instrumental and pedagogical dimensions, we have demonstrated how attending to intentions, processes, and outcomes can illuminate the particular perspectives and manifestations of different forms of STEAM. Although our analysis does not intend to provide a comprehensive review, it does offer a means to further organize our understanding of how STEAM is taken up as it grows as a field.

In attempting to disentangle the variations of STEAM, we have identified a theoretically and methodologically rich vein that not only speaks to the possibility of elevating transdisciplinary pedagogy more broadly, but that also points directly toward strategies for "desettling" structural boundaries of meaning-making privilege in STEM education (Bang et al., 2012; Warren et al., 2020) and empowering equity for rightful presence in previously closed off spaces (Calabrese Barton & Tan, 2019). Studies show that STEAM approaches—and "making" in particular—can provide new pathways for underrepresented and historically marginalized communities to recognize and engage with the implications of these historical and structural legacies (Archer et al., 2019; Calabrese Barton & Tan, 2017; Nasir & Vakil, 2017; Tan & Calabrese Barton, 2018). Furthermore, such approaches may challenge historically rigid constructions of educational discipline priority and hierarchy within the U.S. (and other Western) educational policies and systems, to make education itself more holistic and effective. In building new cross-disciplinary epistemologies of arts and STEM, these approaches to STEAM may hold significant potential to increase efforts to decolonize learning spaces, elevate indigenous knowledge, and prioritize equity as policy means and ends (Land, 2013; McCarthy et al., 2004; Root-Bernstein et al., 2011).

Our perspective on the potential of the mutually instrumental and pedagogical rhetoric of STEAM is informed by the collaborative transdisciplinary work that the authors have both developed and studied over the past decade, which guides our analysis of a field of theory, research, and practice that is still engaging in boundary work (relative to itself and STEM more broadly). While not necessarily disputing that all rhetorics may have their advantages and disadvantages in various contexts, we pay particular attention to the transformative learning potential supported by contexts where STEAM is conceptualized as both pedagogical *and* mutually instrumental, meaning neither the STEM fields nor arts are privileged over the other, but all fields are equally in play with the potential for transforming educational policy and practice. Thus, the fourth rhetoric of mutually instrumental and pedagogical, together with the epistemic practices (Table 1) represents a growing and evolving framework for understanding both STEAM and the integration of the arts and STEM for pedagogy; a needed prompt for productive conversations and imagining of new potential educational futures.

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CONFLICT OF INTERESTS

Jen Wong and Mark Rosin are part-owners of Guerilla Science Global and Bronwyn Bevan is currently a member of its Board of Directors. The remaining authors declare that there are no conflict of interests.

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