Transdisciplinarity in STEM Education: A Critical Review

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Abstract

Science, Technology, Engineering and Mathematics (STEM) education garnered significant attention in recent years and has emerged as a key field of research globally. The goal of this article is to offer a critical review of how STEM education and its transdisciplinarity were defined and/or positioned in empirical studies published during the early formulation of the field. In particular, we sought to identify how these studies conceptualize learners and learning and portray the underlying assumptions in light of the macrosystemic discourses that often serve as ideological forces in shaping research and practice of STEM education. We examined 154 peer-reviewed articles published between January 2007 and March 2018 and analysed them along several emergent dimensions: their geo-spatial focus, focal disciplinary areas, methodological and theoretical assumptions, and major findings. Grounded in a critical transdisciplinary perspective, we used critical discourse analysis to identify how macrosystemic and institutionalized forces — overtly and implicitly — shape what counts as STEM education research, including its goals and conceptualizations of learners and learning. Our analysis highlights the need for aesthetic expansion and diversification of STEM education research by challenging the disciplinary hegemonies and calls for reorienting the focus away from human capital discourse.

Keywords: STEM education; critical theory; transdisciplinarity; discourse analysis

Introduction

In recent years, Science, Technology, Engineering and Mathematics (STEM) education has garnered greater attention in the field of educational research. As reviewed in this article, the number of peer-reviewed publications in English on STEM education grew significantly since 2007. There are also a growing number of books in STEM education research published globally (e.g., Chesky & Wolfmeyer, 2015; Khine, 2018; Langman & Hansen-Thomas, 2017). The meaning and images of STEM education are not monolithic, especially in the context of research and educational practices. Historically, the notion of STEM education has been largely influenced by policies and discourses in the United States (Shanahan, Burke,& Francis, 2016). In the United States, STEM education was emphasized in response to the rising threat for national security during the Sputnik era (Bybee, 2010). In the post-Sputnik area, the discourse around STEM education turned more inward. With the publication of A Nation at Risk (National Commission on Excellence in Education, 1983) the emphasis turned to filling workforce demands in the globalized and dynamically changing market (as represented in Committee on Science, Engineering and Public Policy, 2007).

Globally, STEM education has become intimately associated with its utilitarian and instrumentalist values for economic growth and productivity. The integration of STEM disciplines is identified with "innovation" in scientific, technical and mathematical disciplines. Governmental efforts are well underway in countries around the world to provide institutional support for "innovation" in disciplinary learning at the K-12 levels for example, in China (Li & Chiang, 2019), India (Sharma & Yarlagadda, 2018), Malaysia (Thomas & Waters, 2015), Australia (Sharma & Yarlagadda, 2018), England (Wong, Dillon, & King, 2016), and Canada (e.g., Committee on Science, Engineering and Public Policy, 2007; Council of Canadian Academies, 2015; Shanahan et al., 2016; Science Technology and Innovation Council, 2009, 2015).

There is now a growing attention to critical analyses of the impact of macrosystemic discourses (including neoliberal policies and economic incentives) on STEM education that in turn narrow the scope and meaning of science and science education policy and curriculum (e.g., Carter, 2017; Hoeg & Bencze, 2017a; Vossoughi & Vakil, 2018; Wong et al., 2016). A macrosystem refers to "general prototypes, existing in the culture or subculture, that set the pattern for the structures and activities occurring at the concrete level" (Bronfenbrenner, 1977, p. 515).

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Entrepreneurship and innovation are examples of such macrosystems that have directly shaped practices in technoscientific fields of practice (e.g., technology design) as well as public education. For example, Irani (2019) points out that the push for entrepreneurial approaches to design can lead to the positioning of the work of design (including technology design) as entrepreneurial citizenship that is largely market-driven and consumer oriented. This creates a specific kind of framing of social issues, encouraging people to "translate the injustice around them into programs, products, and services which the private sector could address" (Irani, 2019, p. 216–217), which in turn reframes the members of the public affected by injustice as consumers. This translation creates a pattern of outwardly appearing to solve problems while leaving the sources of those problems untouched. The same macrosystemic forces are in play in the context of public education (Giroux, 2008) which then positions the innovative learner as an entrepreneur and a generator of capital, hidden in the guise of disciplinary authenticity. In the contexts of computing and STEM education, as Sengupta, Dickes, and Farris (in press) argue, such views of learning also tend to rely on technological determinism that foregrounds computational artifacts rather than the inherent heterogeneity of learning experiences (Rosebery, Ogonowski, DiSchino, & Warren, 2010).

Given this backdrop, we examine how contemporary studies of STEM education conceptualize learners and learning and portray the underlying assumptions in light of the macrosystemic discourses that often serve as ideological forces in shaping research and practice at the K-16 levels. Our conceptualization is necessarily political, because the origin and use of the term STEM has been shaped by government policies and initiatives (Shanahan, et al., 2016). It is in this sense that our review distinguishes itself from existing literature reviews on STEM education (e.g., Belland, Walker, Kim, & Lefler, 2017; Kim, Sinatra, & Seyranian, 2018; Reinhold, Holzberger, & Seidel, 2018). In contrast to these reviews, we explicitly attend to questions such as who the learners are, how they are positioned in relationship to STEM, and for whom STEM education (research and practice) is oriented (Philip, Bang, & Jackson, 2018).

We present a review of 154 articles published in 22 English-medium international journals, between January 2007 and March 2018. Our goal was to focus on an early period of STEM education research especially after publication of the report of the US Committee on Science, Engineering and Public Policy (2007), which has played a significant role in setting funding and research initiatives in STEM education. In the period between January 2007 and March 2018, the number of publications showed a significant growth, particularly after 2011 when the number of publications on STEM education exceeded 100 per year. This gave us a substantial corpus of data to select from. Our decision to limit the analysis till 2018 is also based on another interesting turn in the field, because since 2019, there has been an amplification of efforts focused on critical theoretical perspectives in STEM education. This includes special issues in journals by McKinney de Royston and Sengupta-Irving (Cognition and Instruction, 2019), Vakil and Ayers (Race, Ethnicity and Education, 2019) and an edited volume by Sengupta, Shanahan, and Kim (Critical, Transdisciplinary and Embodied Approaches in STEM Education, 2019). Noticeable across these more recent efforts is an explicit attention to political and socio-ecological issues that shape STEM education, in addition to focusing on learners who have been historically marginalized. We therefore assumed that limiting our review to the period between January 2007 and March 2018 would provide an overview of STEM education research in the decade of its early formulation. It also offers us an opportunity to examine how macrosystemic discourses that have shaped policy decisions have influenced scholarship on STEM education during this period, especially when researchers did not explicitly critique these discourses.

In what follows, we first engage in definitional issues around key constructs: integrated STEM education and transdisciplinarity. We then describe how we conducted our literature search and review, both from the perspective of providing an overview of research trends as well as from the methodological perspective of critical discourse analysis. In our findings, we first provide an overview of the current research literature to depict the meaning and image inscribed onto STEM education. Subsequently, by revealing underlying assumptions behind the current research lit-

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erature on STEM education, we depict how macrosystemic and institutionalized discourses are impacting the ways in which current research construes and constructs the images of learners and learning in the sphere of STEM education. We conclude our article by discussing the potentially expansive possibilities of transdisciplinarity, as we envisage spatial and disciplinary expansions and reorientation of the currently dominant discourses on human capital in STEM education research.

Definitional Issues in STEM Education

STEM "Integration": Practice, "Real-World" and Boundary Objects

There have been several initiatives by researchers and policy makers seeking reform in public education that have attempted to define STEM education, which makes creating a precise definition of Integrated STEM Education challenging (Wong et al., 2016). However, across the different definitions we reviewed in the literature, connection between STEM disciplines stood out as a common goal for STEM integration, as well as the emphasis on "real-world" contexts in bringing about such integration.

For example, in a well-cited national report in the US, Honey, Pearson, and Schweingruber (2014) argued that teaching STEM in a more connected manner, especially by contextualizing it in real-world issues, can make the disciplinary practices within the individual STEM disciplines more relevant to students and teachers. In another national report published by the US National Research Council (Duschl, Schweingruber, & Shouse, 2007), the connections within the STEM disciplines were positioned in light of the Science as Practice perspective (Lehrer & Schuable, 2006). In this perspective, conceptual advancement in scientific disciplines is deeply intertwined with advances in representational practices and is positioned as the dance of agency between ideas and the physical world (Pickering, 1995). This perspective, grounded in studies of scientists in action, thus positions science itself as a heterogeneous discipline where measurement and instrumentation, including computational approaches are deeply intertwined with the genesis and refinement of scientific theories and ideas and require multi-disciplinary teams (MacLeod & Nersessian, 2018).

Breiner, Harkness, Jonson, and Koehler (2012) reminds us that the acronym "STEM" stands in for a purposeful integration of the individual disciplines "as used in solving real-world problems (Labov, Reid, & Yamamoto, 2010; Sanders, 2009)" (p. 5). This in turn is based on the notion of authenticity, as STEM professionals are less likely to compartmentalize disciplines in their professional practice (Breiner et al., 2012). The "rupture of the intimate association" (Dewey, 1916, p 294) between disciplines in K-16 classrooms has been long noted to be a problem in public education.

Adopting a more epistemologically grounded approach, Shanahan et al. (2016) noted that integrated STEM education could be viewed in light of Star's (2010) notion of boundary objects: "pragmatic entities valued for their ability to bring collaborators together and facilitate projects and outcomes that might be impossible otherwise" (Shanahan et al., 2016, p. 134). While connections across disciplines is also important in this conceptualization, the metaphor of a boundary object here implies a definition of STEM integration that is neither fixed nor monolithic but partially shared and situationally established among various stakeholders.

Shanahan et al.'s (2016) conceptualization of STEM integration can therefore be seen as an emergent phenomenon — i.e., the synthetic whole that results from disciplinary integration is greater than the sum of its parts. This means that the experience of learning STEM in an integrated manner is different and richer than simply learning multiple disciplines. Recent work has identified what some of these emergent formations might look like. As Sengupta, Shanahan, and Kim (2019) noted, such forms of emergence may be understood through the lens of transdisciplinarity (which we deal with in more detail in the following section), and may

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orient us toward different domains (i.e., forms of phenomena) as the topics of inquiry that are fundamentally more heterogenous than traditionally prescribed curricular topics. Some examples include critical numeracy (Das & Adams, 2019), critical ecological sustainability (Bang & Marin, 2015; Kim, Rasporich, & Gupta, 2019; Lam-Herrera, Ajkem Council & Sengupta, 2019), and macroethics (Philip, Gupta, Elby, & Turpen, 2018; Gupta, Turpen, Philip, & Elby, 2019).

Transdisciplinarity and Critical Perspectives for STEM Integration

In defining transdisciplinarity, we start our discussion by posing a fundamental question: What is discipline? Discipline, as discussed by Pickering (1995), enables humans to extend their conceptual practices: "Disciplines — acquired in training and refined in use — carry human conceptual practices along, as it were, independently of individual wishes and intents" (p. 115). Disciplined ways of using cultural tools and representations (e.g., using disciplined ways of symbols and conceptualizing along with them in algebra) bring humans otherwise-impossible conceptual and representational practices. In this sense, discipline is agentive, enabling, liberating and productive.

Etymologically, the term discipline comes from the Latin word discipulus that originally meant "to educate" but "its connotations over the millennia have shifted considerably to now referring in English to processes of control, at times linked with punishment in one instance and sycophantic allegiance and followers, as in disciplines, in another" (Gordon, 2006, p. 3). Foucault (1977) argued that "discipline produces subjected and practiced bodies, 'docile' bodies. Discipline increases the force of the body (in economic terms of utility) and diminishes these same forces (in political terms of obedience)" (p. 138). That is, discipline turns power into an "aptitude" or a "capacity," a form of capital within the learner that is both increased and focused, while at the same time controlled in scope through a "strict" subjugation of disciplinary practices.

An important mechanism of disciplinary subjugation is also the siloed nature of disciplines in the academy. Foucault (1997/2007) noted that "discipline is a mode of individualization of multiplicities" (p. 12), acting on a multiplicitous whole rather than, first and foremost, on a collection of individuals as was also noted by Dewey (1916) and continues to be largely true to this day. Gordon (2006) frames this issue as disciplinary decadence, noting that the reification of disciplines and the drive to sustain structures and hierarchies within disciplines has led to "the forgetting of their impetus in living human subjects and their crucial role in both the maintenance and transformation of knowledge-producing practices" (p. 4). Human impetus in knowledge-producing practices, its commitment to fundamental societal problems, and living dialogues among disciplinarily-enabled subjects have come to be lost in such a fallacy of constrained and isolated disciplines. This stands in contrast to studies of professional practice in scientific and technological domains — both in research and practice — that highlight the necessity of collaboration and multidisciplinarity (Sobieszczanski-Sobieski, 1995; MacLeod & Nersessian, 2018), uncertainty (Duschl, 2008) and fluidity in professional practices (Sharp & Robinson, 2004) in solving complex "real-world" problems.

These seemingly oppositional connotations of discipline — to educate and to control, to liberate and to constrain, and to create anew and to reproduce — highlight the issue we problematize in this article. If discipline simultaneously affords the abundance of knowings and constrains our knowings, how can we mobilize discipline more toward epistemological and ontological liberation? Historically, the current institutional system of discipline has been entangled with geo-political configuration of the world. As Mignolo (2009) maintains, disciplinary knowledge has long been linked with the colonial matrix of power, truly achievable only by those who are afforded a supposedly neutral view by the privilege of their position atop that hierarchy. Extending Franz Fanon's dictum on language, Mignolo scrutinizes the current and historical disciplinary practices where the geographically marginalized at once "come closer to being a real human being in direct ratio to his or her mastery of disciplinary norms" (p. 165) while also being excluded for fully

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achieving disciplinary personhood. According to Mignolo (2011), breaking the alienation and self-serving reproduction of disciplines requires "epistemic disobedience" (p. 45) against disciplinary coloniality. Epistemic disobedience is led by decolonial thinking, "thinking that de-links and opens ... to the possibilities hidden by the modern rationality" (Mignolo, 2011, p. 46). From this perspective, liberation of discipline is to relinquish geo-political constraints and to aim for expansion of epistemological boundaries.

For us, this act of liberating disciplinary boundaries is the essence of transdisciplinarity. Strong, Adams, Bellino, Pieroni, Stoops, and Das (2016) argue that a "critical transdisciplinary heuristic" (p. 227) that challenges colonial matrix of knowing and being will move science education or STEM education toward "equity, social justice, and polysemia" (p. 235). It should bring into question fundamental elements of the disciplinary infrastructure in light of histories of oppression that typically remain silenced in the canonical representations in disciplinary cultures. For example, Das and Adams' (2019) formulation of critical numeracy illustrates how engaging with histories of and literary work on racialized oppression in the US can challenge the ontological status of numbers as truth, while deepening marginalized students' ownership of disciplinarily valued mathematical practices.

This is a critical, expansive and emergent vision of transdisciplinarity. It is expansive and emergent in the sense that transdisciplinarity is experienced as "reflexive formations and practices" (Sengupta et al., 2019, p. 4), where learning in one discipline can be deepened through engaging with other disciplinary lenses. At the same time, this is not merely an act of seeing more (Higgins, 2008) — rather seeing more critically and historically (Gutiérrez, 2016; Sengupta et al., 2019). Central to such experiences of transdisciplinarity, as Gordon (2006) argued, is the act of teleological suspension, which happens "when a discipline suspends its own centering because of a commitment to questions greater than the discipline itself" (p. 34). Commitment to questions greater than the discipline itself fundamentally requires interactions among disciplinary boundaries that create new places of encounters and interactions, in the same way that the places where fluids meet creates a boundary layer (Shanahan, 2011). The creation of this boundary layer can interrupt disciplinary hegemonies and can also lead to the emergence of new concepts, representations, and applications, that ideally should also re-centre voices from the margins (Sengupta et al., 2019).

For us, an integral part of this work involves interrogating transdisciplinarity "for whom" (Philip et al., 2018). Colourblind and assimilationist efforts do not attend to the cultural heterogeneity in students' work, nor the historical and systemic violence and barriers experienced by students from non-dominant groups (Gutiérrez & Rogoff, 2003; Lee, 2008; Lee, Spencer, & Harpalani, 2007; Rosebery et al., 2010; Martin, 2009). These multi-layered conceptualization of transdisciplinarity in STEM Education guided our critical review of the literature and our review is refracted through this lens.

Transdisciplinarity and Discourse

Central to our work is the positioning of STEM Education research itself as discourse. As Kelly (2014) pointed out in the context of science education, discourse entails more than the words and phrases used for the communication of ideas, bringing into view how communities "collectively construct norms and expectations, define common knowledge for the group, build affiliation, frame knowledge made available, provide access to disciplinary knowledge, and invite or limit participation" (p 321). The study of classroom discourse has long been a mainstay in science and mathematics education, as it reveals: how affiliation and identity are constructed through language-in-use (e.g., Herbel-Eisenmann, Wagner, Johnson, Suh, & Figueras, 2015; Langer-Osuna & Esmonde, 2017; Shanahan & Nieswandt, 2011), how students and teachers engage in conceptual and representational practices central to doing science and mathematics (e.g., Lemke, 1990; Moschkovich, 2007; Rosebery et al., 2010; Sengupta, Dickes, & Farris, 2018; Sfard, 2007), and the role that ideologies play in shaping disciplinary engagement (Philip et al., 2018).

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Rather than focusing on classroom discourse as practiced in the articles we reviewed, we use discourse analysis to demonstrate how ideologies around global competitiveness and innovation for capital production have shaped the discourse of STEM education research in terms of relationships between the constituent disciplines. Our work arises from the concern that ideological positionings of STEM in classroom discourse also shape opportunities for disciplinary learning (Slaton, 2001; Philip et al., 2018). For example, ideological assumptions that technical knowledge (e.g., structural issues related to building construction) is unrelated to human well-being (e.g., who are being served in the building and how) can limit the scope of learning in an engineering course (Slaton, 2001). For our purposes, this is also related to conceptualizations of transdisciplinarity, because a discipline that brings together both structural engineering and careful considerations about human experiences is fundamentally more complex than any discipline that would focus singularly on any one of these dimensions. Furthermore, such ideological positionings may also shape the language-in-use in classrooms (Philip et al., 2018), and this is particularly significant given that science and mathematics educators have shown the importance of paying attention to (and supporting) heterogeneity in students' language use, while also illustrating how specific forms of discourse in the classroom can also limit participation (Kelly, 2014; Rosebery et al., 2010; Takeuchi, 2016). In other words, our concern is that ideological positionings of STEM may have been intrinsically shaping conceptualizations of transdisciplinarity in STEM education research, and along with it, opportunities to participate in learning in classrooms.

Our overarching view of discourse is based on Foucault (1991) who argued that analyzing discourse is not about understanding the forms of language or uncovering hidden meanings buried within it. Foucault treats discourse as "a monument to be described in its intrinsic configurations" (p. 60). The notion of discourse as a monument emphasizes its materiality that emerges from particular conditions and shapes and redefines the contemporary practices that follow from it, for example, by setting the "limits and forms of the sayable" (p. 59). In this view, discourse is not a window into the minds and thoughts of those who created it but an edifice that can be used to understand the field in which it was created and deployed.

While keeping our central focus on the value of examining discourse as a monument, enlarging our framing from Foucault to take a broader critical discourse analysis perspective enables us to further scrutinize texts in terms of "how social agents make or 'texture' texts by setting up relations between their elements" (Fairclough, 2003, p. 11). Hall (1992) emphasized the importance of attending to relationships to power when making sense of discourses and ideologies, because "it is power, rather than the facts about reality, which makes things 'true'" (Hall, 1992, p. 203). Thus, discourse can both enable and limit ways in which a certain topic (in our case, for example, STEM education) is constructed and practiced, and it is along these lines that Philip et al. (2018) demonstrated how ideological convergence and expansion limits or expands opportunities for learning in STEM classrooms. As Luke (2019) notes, critical discourse analysis allows us "to see how broader formations of discourse and power are manifest in the everyday, quotidian aspects of texts in use" (p. 10). Dominant discourses around the role of science in society shape languages and practices in STEM education research and policy. In this article, we therefore use this multifactorial discourse analysis approach to demonstrate how macrosystemic discourses are shaping the discipline of STEM education and propose ways how we can mobilize such boundaries through the conceptual tool of transdisciplinarity.

Methodology

Inclusion Criteria

Our literature review covers the period between January 2007 and March 2018 and we created two sets of databases. The first database was to gauge trends in the number of publications on STEM Education over time. For this analysis, we used the database EBSCO Academic

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Search Complete that encompasses academic journals in the field of education (beyond our target journals for the second database). We conducted keyword search to see the number of publications that include "STEM education" or "STEM learning." Our search was limited to peer-reviewed journal articles that were published in English for a period of 10 years between January 2007 to December 2017 (in order to create a database of an exact 10 years period, we did not include any publications between January to March 2018). The total number of publications in this database was 2,171 articles. We created the second database for close review of articles in 22 English-medium international journals (see Appendix). First, we selected relevant journals ranked in the top 100 in the Scimago Journal and Country Rank (SJR) within the field of education, as of March 2018. Among these journals we decided to focus on articles in science education, mathematics education, and the learning sciences. We decided to focus on science and mathematics education because scholarship on integrated STEM education builds directly on the published research in these fields, and they are also integral components of STEM education. Furthermore, science and mathematics are well edified in K-12 curricula, both nationally and internationally, whereas computing and engineering education are only beginning to find their places in K-12 classrooms. In addition to the SJR, after consulting with colleagues in science and mathematics education, we added other impactful journals that are not ranked in the top 100 in SJR as of 2018.

For 21 out of 22 journals (except for the International Journal of STEM Education, as explained later in this paragraph), we identified relevant articles for our review, by using the following search keywords in article titles, keywords, abstract or texts (excluding references): "STEM education," "STEM learning," and "STEM reform." This selection criterion does not allow us to collect all the published studies in the STEM education field, as there are studies that involve transdisciplinary approaches in STEM education but do not label themselves as STEM. Nonetheless, we intentionally limited our search this way, in order to understand the meanings researchers have attached to the very term, STEM, in relation to education, learning and educational reforms. Using this method, a total of 140 articles were selected for review. Among the 140 articles, 10 articles were non-empirical and either a literature review or a discussion paper. We used these 10 articles for broader discourse analyses but excluded these from the descriptive statistics presented in the Findings section. In addition, we reviewed articles published in the International Journal of STEM Education because the journal explicitly focuses on STEM education. For this journal, we looked for the special issue topics as well as the "hot topics" that were identified by the journal. Fourteen articles published in the journal's special issues were selected for our close review. One of these articles was a literature review and was thus excluded from descriptive statistics. In total, we closely reviewed 154 articles and among these, 143 empirical study articles were used for descriptive statistics presented in the Findings section.

Analysis

The first phase of our analysis involved emergent coding and descriptive statistics analysis to explore the theoretical assumptions, research questions, methodology, major findings, and disciplinary areas of each of the empirical studies included in our sample (n=143). This analysis provided an overarching picture of the emergent orientation across the studies. To dig deeper into the power of the underlying orientation of these studies, our second and third phases of analysis employed critical discourse analysis (Fairclough, 2003; Foucault, 1991; Hall, 1992; Luke, 2019) to examine assumptions, ideologies and potential power relationships in the context of STEM education. As we explained above, the articles we reviewed for this phase included theoretical, review and position papers (n=154). Our focus was on identifying the directions of research and ideological influences that were shared among the articles, and our analysis revealed the strong influence of the Next Generation Science Standards (NGSS). The third phase of our analysis was another round of critical discourse analysis focused on the ways in which the articles used the definitions and framings of the NGSS documents. We describe each phase in more detail next.

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Phase 1. First, we read each article and took reading notes focusing on the following areas: a) theoretical assumptions, b) research questions, c) methodology, d) major findings, and e) disciplinary areas. The goal of this analysis was to present a detailed overview and trend of published articles on STEM education along these dimensions. These notes, along with PDF files of the articles were imported into NVivo (QSR International Pty Ltd, 2018). We reviewed the articles independently and met together several times to discuss and solidify the codes. Each article was reviewed by at least two researchers. Twenty percent of the cases were then selected to establish an inter-rater reliability. Two researchers independently coded these cases and we established an agreement rate of 98% and an inter-rater reliability of .85 (Krippendorff's alpha), which indicates strong agreement.

Phase 2. In the second phase of our analysis, we analysed how "broader formations of discourse and power" (Luke, 2019, p. 10) manifest themselves in the descriptive statistics in Phase 1. We also employed discourse analysis tools introduced by Fairclough (2003), such as habitual collocation (i.e., habitual patterns of connecting words that are immediately one to three words away), grammatical mood (i.e., assertive, interrogative, or imperative), legitimatization (i.e., different strategies to legitimatize argument), and nominalization and metaphorical representations. We reviewed articles together, and we had multiple meetings to discuss particular articles and solidify our analyses guided by critical discourse analysis. This led us to identify two thematic elements that capture and illuminate much of what constitutes the monument of STEM education discourse: the influence of NGSS and pipeline metaphors.

Phase 3. To further examine these two thematic elements (the influence of NGSS and pipeline metaphors), guided by critical discourse analysis, we also examined whether there is any contradiction in the rhetoric in the texts. Through such analysis, we collectively came to understand what counts as acceptable, as well as what counts as unsayable (Foucault, 1977; 1991) in the current STEM education research literature, including how pipeline metaphors have become and frequent and problematic discourse element. This phase of analysis also involved identifying conflictual epistemologies as reflected in the theoretical framework, discussion and implications in each article. We analysed the percentage of articles that cited the NGSS documents (such as NGSS Lead States, 2013), how NGSS was mentioned and positioned in the articles, as well as the ways in which those documents set up relations between their linguistic elements.

Findings

Trends in STEM Education Publications

Figure 1 shows the trend in terms of growth in the number of publications between January 2007 and December 2017 (total number: n=2,171). As seen here, the number of peer-reviewed publications on STEM education grew significantly over this period. For example, in 2017, the number of publications increased by a factor of 20 compared to 2007.

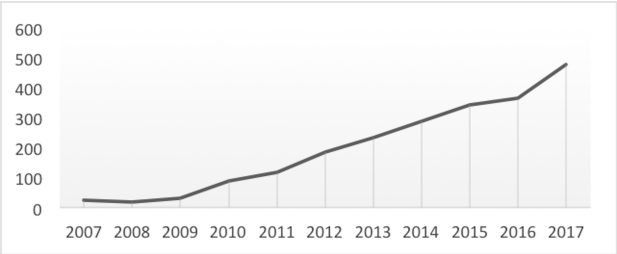

Figure 1: Number of publications using "STEM education" as a keyword (2007-2017).

We also found that the key words "STEM education," "STEM learning," or "STEM reform"

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have been taken up much more frequently in science education journals than mathematics education journals or general education journals (Figure 2): 91 articles were published in science education journals, compared to 11 articles in mathematics education journals, and 38 articles in general education journals. As seen in Figure 2, some major mathematics education journals (Educational Studies in Mathematics, For the Learning of Mathematics) did not have any articles found with the key word search of "STEM education," "STEM learning," or "STEM reform." This discrepancy in the ways in which "STEM" was taken up between the science education community and the mathematics education community suggests how STEM education has been predominantly shaped by the science education community and the scholarly discourse within science education.

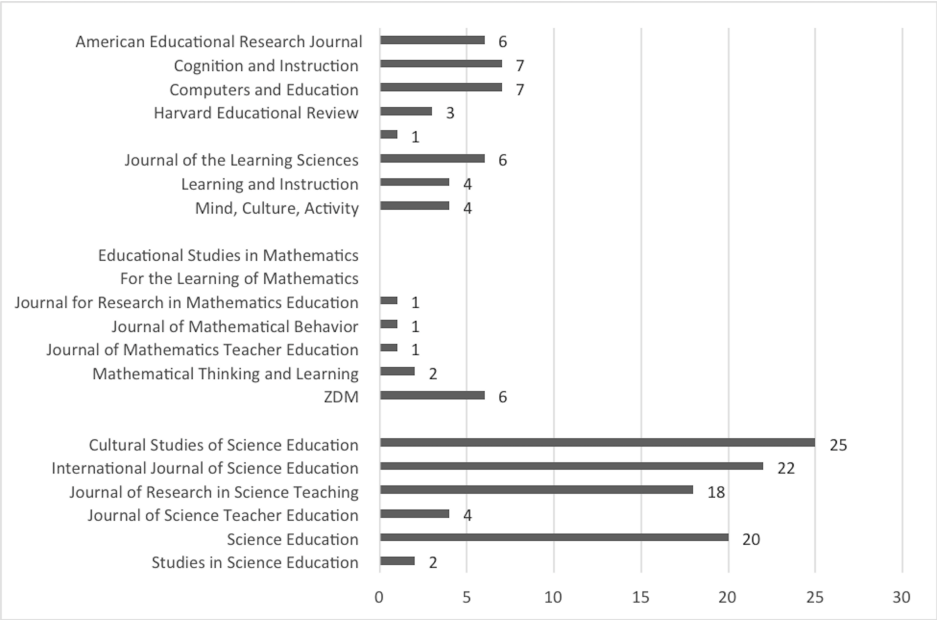

Figure 2: Number of publications using "STEM education" as a keyword (2007-2017).

Transdisciplinarity (or the Lack Thereof) in the Current STEM Education Research

Our examination of the disciplinary concepts and areas that the studies focused on reveals a dearth of studies that can be considered as interdisciplinary and/or transdisciplinary. As defined earlier, interdisciplinarity refers to amalgamation of two or more disciplines, whereas transdisciplinarity goes beyond the amalgamation; the relationship among disciplines is not additive, rather reflexive and emergent. In addition, questioning hegemonic disciplinary assumptions and practices is also at the core of our definition of transdisciplinarity. Examples of such transdisciplinary research include community-based design research by Bang and colleagues (Bang & Marin, 2015; Bang & Medin, 2010) that question the "settled" nature of epistemologies of Western science through centralizing Indigenous cultural practices, epistemologies and ontologies. Philip et al. (2018) presented an axiological challenge to normative curricula and pedagogies in engineering education by questioning and making explicit its underlying militaristic ideologies in the undergraduate classroom. Each of these articles present an expansive re-imagination of disciplinary work by revealing hegemonic traditions within the discipline while also offering critical historical re-orientations (Ahmed, 2006). This brings new forms of phenomena within the purview of the disciplines, as well as deepens engagement with concepts and practices that

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are traditionally viewed as central to the disciplines. However, evidence of such critical and expansive conceptualizations of transdisciplinarity was absent in our current database.

Despite the implied sense of interdisciplinarity in "integrated" STEM education, we found that only five studies (out of 143) were considered to be interdisciplinary in terms of their explicit emphasis on two or more disciplines. For example, Berland and Steingut (2016) measured students' intrinsic motivation in a year-long engineering, mathematics and science course that incorporated multiple design challenges such as designing and building a pinhole camera and analysing data to redesign a model wind turbine. Clark, Sengupta, Brady, Martinez-Garza, and Killingsworth (2015) centralized the concept of disciplinary integration in their design of digital games to support students' scientific practice. In their design, players (learners) iteratively develop and design computational and mathematical representations in the context of modelling Newtonian motion. Burgin, McConnell, and Flowers (2015) organized a research apprenticeship program for high school students to work on biofuels-related research projects in university chemistry and engineering laboratories. Geiger et al. (2018) focused on the interdisciplinary collaboration among scientists and mathematicians in the process of developing a STEM Education module focusing on modelling. Lamb, Akmal, and Petrie (2015) described students' self-efficacy through the integrated STEM learning, incorporating direct STEM integrated instruction, Lego Robotics, the Architects in Schools Program, and partnership with the National Air and Space Museum.

Aligned well with the prevalence of STEM education articles in science education journals compared to mathematics education journals, STEM education was largely situated in studies on learning and teaching of sciences (n=45) rather than studies of learning and teaching of mathematics (n=14) (see Figure 3). Even in the articles situated in mathematics education, mathematical representations and practices were defined as STEM because of their applicability to the discipline of science (as seen in Jones, 2015; Ruthven & Hofmann, 2013; Schuchardt & Schunn, 2016). The practice of science as modelling — which is also one of the defining paradigms in contemporary science education (Duschl & Grandy, 2008; NGSS Lead States, 2013) — largely served as the epistemological anchor in which such forms of interdisciplinarity were grounded. In contrast, the articles focusing on the concept or practice of science tended not to draw a connection with the discipline of mathematics. What counts as mathematical expertise, for example, as reported in studies of expert mathematicians (Schoenfeld & Herrmann, 1982; Wilkerson & Wilensky, 2011), was not consulted within these articles. Instead, in these articles, disciplinary practices in science education were redefined as STEM education by making explicit the connection between scientific modelling as a design-based practice and the practices of engineering design, as set out in the NGSS standard (as seen in Capobianco, DeLisi, & Radloff, 2017; Chabalengula & Mumba, 2017; King & English, 2016; Peterman, Daugherty, Custer, & Ross, 2017). We can therefore conclude that across the studies we reviewed, the discourse in science education predominantly shaped what counts as integrated STEM education.

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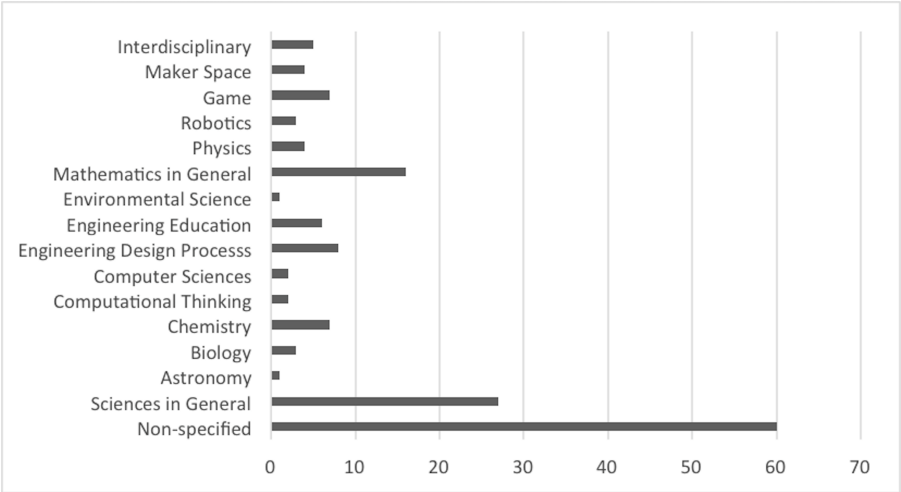

Figure 3: Number of publications on STEM education according to disciplinary areas. *Note.* Multiple-coding was possible.

Another interesting finding concerns the prevalence of computational modeling, making and maker spaces, and robotics. Although the notions of tinkering, play, digital games, robotics and the use of computational modeling in science and mathematics education has a longer history (Kafai et al., 1996; Papert, 1980; Resnick, Eisenberg & Berg, 2000; Turkle and Papert, 1991; Wilensky & Reisman, 2006), explicit attention to interdisciplinarity in the context of integrating computing with STEM education is both relatively scarce and recent. For example, despite the growing attention of computational thinking in STEM education (e.g., diSessa, 2018; Khine, 2018; Sengupta, Kinnebrew, Basu, Biswas, & Clark, 2013), we only found a few studies that focused on computational thinking and modeling with the explicit mention of STEM education. Wilkerson-Jerde, Wagh, and Wilensky (2015) conducted design-based research by introducing DeltaTick, the agent-based modelling platform they developed. Sinclair and Patterson (2018) documented students' computational thinking practices, in mathematics classes utilizing the Geometer's Sketchpad. In the context of K-12 computer sciences education, Philip, Olivares-Pasillas, and Rocha (2016) examined whether and how students attend to the racialized histories and context of data as they engage in data visualization. In the context of learning science using digital games, Clark et al. (2015) integrated computational representations in players' experiences.

In the context of learning through making, we found that the direct influence of science education was less prevalent. Pinkard, Erete, Martin, and McKinney de Royston (2017) described an after-school program where non-dominant middle school girls designed digital media and using various forms of art and computational circuits. The focus of this study was not on learning about the physics of electricity, rather it was on supporting the development of marginalized students' computing identities. DiGiacomo and Gutiérrez (2016) led an after-school program in a low-income predominantly Latino suburban community. In their program, students engaged in maker activities to make and tinker with Squishy Circuits or Scribbling Machines. Similar to the study by Pinkard et al. (2017), learning within the disciplines of science or computer science was not the focus of the authors' inquiry; instead their emphasis was on identifying the role that "relational equity" played in supporting tinkering. However, despite the lack of direct attention to science and mathematics education research, the centrality of electrical circuitry and computational work as the anchors of integrated STEM in both these studies suggest that technologies that were initially designed within the purview of science (and mathematics) education are now being positioned as the locus of integrated STEM education.

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The lack of clear or specific focus on disciplinary concepts and topics (e.g., force and motion or chemical reactions in science education; derivatives and quadratic functions in mathematics education) across the articles we reviewed, however, is a robust finding in our analysis (see Figure 3). Generally, these studies (which we categorized as "non-specified") focused on students' future career visions and choices with regards to STEM disciplines, instead of students' learning of particular concepts or learning experiences within specific courses. This in turn implies that "STEM education" was predominantly positioned as a context where learners' STEM identities and making practices were investigated with a clear emphasis on workforce or career readiness, but without a focus on disciplinary concepts and practices that were in play during the learning experiences.

Assumptions Underlying "Integration": Further Problematizing Interdisciplinarity and Transdisciplinarity

In this section, we interrogate the epistemological assumptions that underlie notions of integration and interdisciplinarity in STEM education. We first identify where the studies were conducted, with what age groups, and methodological and theoretical framings of these studies. We then present a critical discourse analysis of the influences of NGSS in shaping STEM Education research, partly due to the dominance of US-based research and publication venues. Along this line of analysis, we also examine some of the prevalent metaphors that are shaping the current discourse in STEM education research. Overall, this section reveals the nature of hegemonic practices that have shaped (and continues to shape) STEM education research.

Colonial matrix: Countries where studies were conducted

Out of the 143 empirical studies that we reviewed, 88% or 126 articles were conducted in the United States, followed by England (n=3), Australia (n=2), Belgium (n=2), and Norway (n=2). Other countries include Brazil, Canada, Denmark, Israel, Slovenia, South Africa, Sweden, and Turkey, and only one study involved more than one country. With our current search criteria, we noticed that no article represented STEM education in Asia.

This overwhelming focus on the United States could be partially because our search focused on English-medium publications, but also probably because the notion of STEM education originated in the United States historically (Shanahan et al., 2016). As Shanahan et al. (2016) argued, the emphasis on STEM education in the United States has historically been rooted in concerns for national security and militarization, as evident in A Nation at Risk published in the post-Sputnik era (National Commission on Excellence in Education, 1983). In Charting a Course for Success: America's Strategy for STEM Education, a government-issued publication in 2018, we can observe how the urge for national security continues to shape visions for STEM education in the United States:

> Since the founding of the Nation, science, technology, engineering, and mathematics (STEM) have been a source of inspirational discoveries and transformative technological advances, helping the United States develop the world's most competitive economy and preserving peace through strength. The pace of innovation is accelerating globally, and with it the competition for scientific and technical talent. Now more than ever the innovation capacity of the United States — and its prosperity and security — depends on an effective and inclusive STEM education ecosystem (Committee on STEM Education of the National Science and Technology Council, 2018, p. v).

As evident in this vision statement, nationalistic discourse — characterized by the dual focus on national security and economic competition — is central to defining and positioning STEM education as an area worthy of immediate attention across the United States. However, in

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the articles we reviewed, the influences of national security or militarization are not mentioned overtly, except for Philip et al. (2018), who explicitly analysed the intersection between ideologies and engineering students' disciplinary learning.

Drawing from Mignolo (2009), we had problematized disciplinary practices as hegemonic in light of their historical links with the colonial matrix of power and the geo-political configuration of the world. The current dominance in the United States context in STEM education research implicitly perpetuates such geo-political configuration of epistemology and axiology to define the discipline of STEM education.

Methodological assumptions

A particular pattern that emerged in our analysis is the predominant focus on secondary and postsecondary education (as seen in Figure 4). As we will discuss more in the following section, nearly all of these studies confine their methodological scope to relatively short time periods in students' lives. This stands in contrast to Roth and Eijck's (2010) call for shifting our methodological focus to longer time scales. They compiled their studies across diverse age ranges (from Kindergarten children to postsecondary students) and proposed "fullness of life" as the unit of analysis. They wrote:

> To understand lifelong, life-deep, and life-wide STEM learning, we need models and theories that capture the phenomenon of interest both in the concrete instances that it realizes itself (synchronically) and over long periods of time (diachronically) (p. 1040).

In our review, we found that none of the studies considered "fullness of life" in their methodological approaches. This was also evident in the form of lack of attention to the early years or out-of-school or post-formal schooling context such as studies on parents and professional settings.

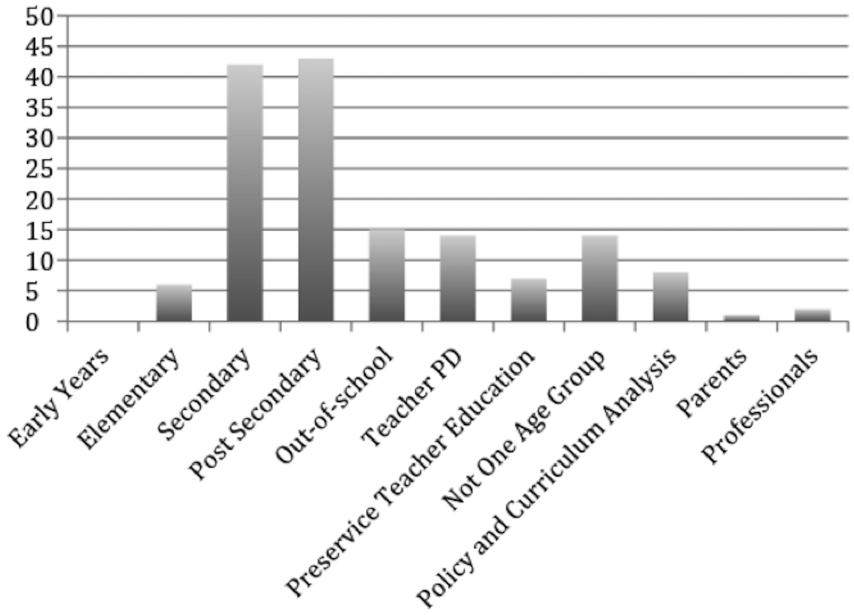

Figure 4: Number of publications and context of study.
Note: If age group was specified for Out-of-School, the study was coded multiple times (e.g., Out-of-School/Elementary).

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As shown in Figure 4, most studies were conducted in postsecondary (n=43) and secondary contexts (n=42). Significantly fewer studies focused on elementary grades and the early years (i.e., Pre-Kindergarten and Kindergarten through Grade 3). Only six studies explicitly focused on STEM education in elementary grades and none of the studies focused exclusively on the early years. A number of studies were conducted with multiple age groups (n=14), some of which include students in the early years or elementary school. For example, DiGiacomo and Gutiérrez's (2016) after-school program involved Grade 2 to Grade 5 students. However, most of the studies categorized for "not one age group" studied the program for upper elementary school to secondary students. The studies on teacher professional development (n=14) and pre-service teacher education (n=7) were further broken down into elementary teacher education (n=7), secondary teacher education (n=10), postsecondary education (n=1), when the context was specified. Overall, these findings point to a relative lack of attention to STEM education in the early years and lower elementary grades. We speculate that this skewed focus on secondary and postsecondary contexts relates to the preponderance of another research theme — STEM career choices or career preparedness — which orients the research focus on whether secondary and postsecondary students are being prepared to choose or are going to choose further studies and/or professionalization in STEM disciplines. We will further investigate this point in a later section where we focus on how the pipeline metaphor has shaped research in STEM education.

Other contexts that are relatively under-examined include professional practice in STEM or STEM-related disciplines (n=2) and professional practices of parents of school-aged children in STEM or STEM-related fields (n=1). Azevedo and Mann (2017) studied the practices of amateur astronomers focusing on their embodied action and reasoning. Skinner et al. (2018) conducted a study on intelligent training systems for surgeons on robotic assisted laparoscopic surgery. The STEM-related practices that families of school-aged children engage in their everyday lives also have not been examined, with the exception of Civil (2016) who investigated how parents' mathematical practices and professional practices (e.g., welder, mechanic, seamstress) can shape their children's disciplinary engagements.

Overall, compared to classroom-based studies (including those that focus on teacher education and teacher professional development), a much fewer number of studies focused on out-of-school settings (in school: n=112; out of school: n=15). Some examples include STEM education initiatives designed in out-of-school contexts include a community-based summer camp with indigenous communities (Bang & Medin, 2010), a summer institute on youth participatory action research for environmental studies (Mark, 2017), Maker Faires (Dixon & Martin, 2017), and afterschool programs for digital media making and making/tinkering (DiGiacomo & Gutiérrez, 2016; Pinkard et al., 2017). Only one study in our database focused on bridging learning across formal and informal settings. Adams and Gupta (2017) investigated the affordances of an informal science institution in supporting teacher candidates understand how people learn and how to engage with diverse learners.

We believe that these patterns observed in contexts of study are also related to the methodological approaches adopted in the studies (see Figure 5). The most frequently chosen methods in our current database were surveys (n=27, 18.8%), case studies (n=24, 16.7%), and interviews (n=20, 13.9%). The types of surveys used include students' self-reporting in questionnaires, students' achievement test data from high-stakes tests, and psychological assessments (e.g., self-efficacy questionnaire). For example, Andersen and Ward (2014) used the High School Longitudinal Study of 2009 in the United States and examined racial differences in the relationship between students' future plans to pursue STEM-related disciplines and students' evaluation of themselves as a science or mathematics person on a questionnaire. We take this issue up again in a later section, as we discuss the correlation between the use of these methodological approaches and use of the pipeline metaphor. We also found that overall 22.2% (n=32) articles did not specify the methodological frameworks or approaches. In contrast, 87.8% of the articles identified their methodological frameworks explicitly, demonstrating a range that includes decolonizing methodology, hermeneutics, participatory action research, and design-based research.

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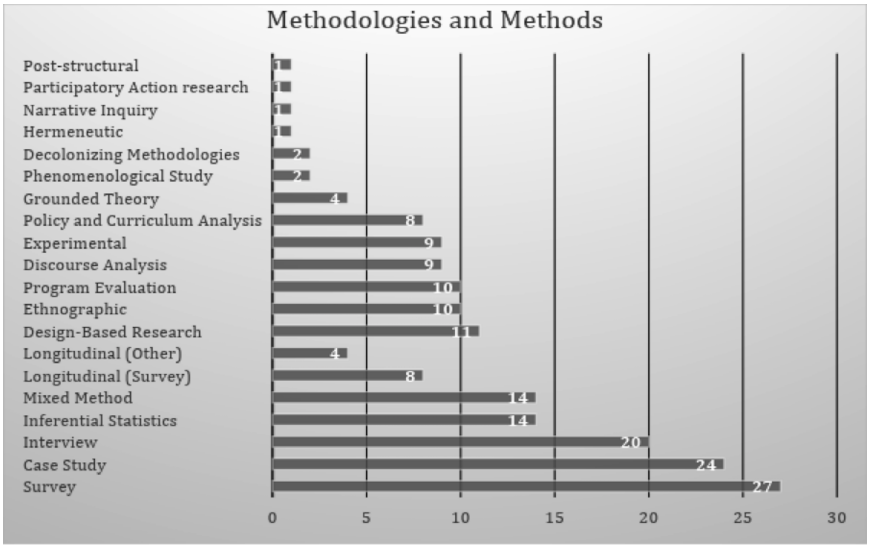

Figure 5: Methodologies and methods used in STEM education research. Note. Where appropriate, a coding was coded in multiple ways.

This methodological diversity suggests the co-existence of several divergent ontologies and epistemologies within the field of STEM education research that cannot be easily reconciled. In survey-based studies (n=27), certain attributes of learners (e.g., gender, race, socioeconomic status) tend to be treated as independent variables (e.g., Andersen & Ward, 2014; Bottia, Mickelson, Giersch, Stearns, & Moller, 2017; Cerinsek, Hribar, Glodez, & Dolinsek, 2013; Sahin, Ekmekci, & Waxman, 2017). Drawing from a large number of samples of learners, these studies highlighted how race, gender and socioeconomic status affect students' aspirations to pursue STEM-related disciplines and careers. In contrast, focusing on a small number of learners, studies drawing upon from phenomenology (McGee & Bentley, 2017), narrative inquiry (Craig, Verma, Stokes, Evans, & Abrol, 2018), or ethnography (Allen & Eisenhart, 2017; Nasir & Vakil, 2017) elucidate in what ways students' identities and STEM-related disciplines become intertwined. For example, McGee and Bentley (2017) illustrate salient events that highlight the pervasiveness of racism, sexism, and race-gender bias for Black women in STEM disciplines. Instead of taking race, gender and socioeconomic status for granted, these studies try to understand the intersectional contexts in which learners' identities become salient in their STEM learning experiences.

We found a methodological convergence between design as a pedagogical approach and design-based research as a methodological approach (Bang & Marin, 2015; Carreira & Baioa, 2017; Clark et al., 2015; Gaydos & Squire, 2012; Geiger et al., 2018; King & English, 2016; Nasir & Vakil, 2017; Pinkard et al., 2017; Ruthven & Hofmann, 2013). In these studies, design was also the practice that learners engaged in, thus positioning design as a fundamentally interdisciplinary practice that can integrate STEM disciplines. For example, some researchers engaged in the design of new technologies for STEM education such as disciplinary-integrated games, and students in their studies also engaged in designing games and models for science learning (as seen in Clark et al., 2015; Gaydos & Squire, 2012).

Other researchers designed social infrastructures to support marginalized students' engagement with STEM beyond the traditional school contexts (Bang & Marin, 2015; DiGiacomo & Gutiérrez, 2016; Pinkard et al., 2017). Such design efforts are aligned well with the notion of social design (Gutiérrez & Jurow, 2016), where social justice is central to both the experience of learning and conceptualizing what STEM education can look like. Social design involves social transformation that "is sought by creating a significant reorganization of systems of activity in which participants becoming designers of their own futures" (Gutiérrez & Jurow, 2016, p. 566).

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Along similar lines, Nasir and Vakil (2017) explicitly connected ethnographic methodology and design-based research in their methodology, combining ethnographic description of how it is with design of how it can be could move the research toward development of new tools, programs, and technologies, from the close relationships between researchers and participants. However, it is also important to note that barring these few studies, such methodological convergence between design, social justice and design-based research was not explicit in our current database.

There were relatively few studies that followed students or programs longitudinally, i.e., for more than a year (n=12 or 8.3%). One group of the longitudinal studies (n=8) was based on surveys, questionnaires and student achievement data. For example, Bottia et al. (2017) used longitudinal data on students' academic performance and scholastic experiences obtained from the North Carolina Roots of STEM Success project. They analysed how the racial composition of the school influenced students' decision to major in STEM, and how this influence evolved longitudinally. Sadler, Sonnert, Hazari, and Tai (2012) examined gender differences in terms of the fluctuations in STEM career plans during the high school years. Another group of the longitudinal studies (n=4) drew from ethnographic methodology (Allen & Eisenhart, 2017; Roth & Eijck, 2010; Weis et al., 2015) and program evaluation (Falk et al., 2016). For example, Weis et al. (2015) presented the rise and erosion of STEM education reform based on a three-year comparative longitudinal and ethnographic study in two cities in the United States, Buffalo and Denver. Falk et al. (2016) depicted the program they designed and led, Synergies, an ongoing effort to enhance STEM learning in school and out of school, in a diverse, under-resourced community in Portland, Oregon. Overall, across the articles, we found scant attention to "thick description" (Geertz, 1973, p. 7) of the learning experiences that happen across the lifespan.

The Influence of NGSS

Out of the 154 articles (including non-empirical articles) that we reviewed, 47 articles positioned NGSS as one of the key motivations behind their studies. Set in the context of the United States, NGSS frames Grade 1–12 standards for physical sciences, life sciences, earth and space science and engineering, technology and applications of science. Considering the final version of NGSS was released in April 2013 and our review covers the time range between 2007 and 2018, the hegemonic influence of NGSS in the current STEM education literature, internationally, is worth examining.

We analysed the way researchers were oriented in relation to NGSS along a few different dimensions. First, the current STEM education research is predominantly geographically oriented toward the United States, because most of the articles used NGSS to define or mention competencies and skills associated with STEM learning. Two notable examples include "design" or "engineering design process," which are regarded as key competencies in NGSS (e.g., Balgopal et al., 2017; Capobianco et al., 2017; Faber, Hardin, Klein-Gardner, & Benson, 2014), and the "nature of science" (e.g., Adibelli-Sahin & Deniz, 2017; Burgin et al., 2015).

However, the extent to which these articles used NGSS differed. Some articles designed their studies by centralizing the relevant NGSS standards such as the teacher professional development and assessment rubric (Chabalengula & Mumba, 2017; Nugent et al., 2015; Tekkumru-Kisa & Stein, 2017; Varelas et al., 2018). Other articles briefly mentioned the key practice or competencies defined by NGSS (e.g., focusing on problem solving skills, analysing and interpreting data, and defining content of STEM teaching) to contextualize their studies or findings. For example, mentioning NGSS performance expectations, Wild (2015) contextualized his findings on a correlation between students' career expectations in sciences and their perception on learning environment as follows:

> Despite the challenges, the current wave of curriculum reform outlined in the Next Generation Science Standards (NGSS) (Achieve, 2013) may nudge teachers to facilitate more constructivist classrooms. (...) Moreover, the NGSS performance expec-

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> tations require students to integrate scientific practices, core disciplinary ideas, and cross-cutting concepts. (...) Although it remains to be seen how the NGSS will affect classrooms, the considerable overlap between features of a constructivist learning environment and the vision of the Standards provides glimmers of hope for more equitable science education (Wild, 2015, p. 2299).

What is not made explicit in this type of rhetoric is the possibility of how NGSS performance expectations could hinder "equitable science education," despite the latter being described as a desirable outcome. For example, career expectations, a construct that was used to measure the success of "constructivist classrooms" in Wild's (2015) study, does not account for or focus on the actual learning experiences of the students. These authors argue that NGSS emphasizes cross-cutting scientific practices and is therefore aligned with constructivist approaches, but they do not take into account if or how NGSS guidelines, based on how they are interpreted and implemented in the classroom, can limit the scope of learning experiences. For example, Pruitt (2014) identified the difference between adoption and implementation in classrooms as a key challenge of praxis, and Philip et al. (2018) have also argued that adoption of national curricular mandates and expectations without considering carefully the underlying political ideological forces and assumptions can be deeply problematic. We revisit this issue in more detail in the following subsection.

We also analysed "legitimation strategies" (Fairclough, 2003, p. 88) used in researchers' rhetoric in relation to NGSS. We found that NGSS was often treated as an authoritative mandate and a set of objective standards to be followed. The following excerpt from Faber et al. (2014) is an example of such a use of NGSS to justify the significance of their research findings:

> The Next Generation Science Standards place a focus on science and engineering practice with the goal of reflecting what scientists and engineers do as they explore, design, and build (NGSS Lead States, 2013). Given this new emphasis on science and engineering practice, it is important for teachers to take part in PD experiences that encourage their development of scientific expertise and their understanding of scientific practice (Faber et al., 2014, p. 803)

In this text, the habitual collocation discussed by Fairclough (2003) suggests that the visions and practices promoted by NGSS were described with lexicons such as "emerging," "recent," "key," and "new." This collocation pattern implied the significance and urgency of NGSS, and in association, the significance and urgency of the particular research foci. The following excerpt is another example that illustrates this point:

> The Framework for K-12 Science Education (NRC, 2012) and the Next Generation Science Standards (NGSS Lead States, 2013) bring a new vision for science teaching and learning. This vision is based on key findings from research (NASEM, 2015) such as integrating knowing and doing is key for science learning (e.g., Pickering, 1992) and developing understanding through engagement in scientific practices is more productive for future learning than memorizing facts (e.g., Cognition and Technology Group at Vanderbilt, 1993)" (Tekkumru-Kisa & Stein, 2017, p. 1, emphasis added).

Here NGSS was treated as an authoritative document which will "bring a new vision for science teaching and learning," backed by "key findings from research." The inclusion of STEM researchers (e.g., researchers in engineering) in the committees that drafted NGSS was also presented as another reason for positioning NGSS in an authoritative stance, as evident in the following excerpt:

> It is noteworthy that, in the United States, discipline-based researchers in engineering and natural sciences ensured that disciplinary practices and competencies were presented alongside each other in the most recent revision of the national science

> education standards for school-aged students (Balgopal, Casper, Atadero, & Rambo-Hernandez, 2017, p. 1626).

A few articles, however, adopted a more critical stance (Garibay, 2015; Hoeg & Bencze, 2017b; Storksdieck, 2016; Zeidler, 2016; Zouda, 2018). For example, based on critical discourse analysis of NGSS, Hoeg and Bencze (2017b) concludes:

> Our analysis of the NGSS indicates that it is a set of standards that prioritize measurable and reproducible performances. The NGSS appear to be based on a conception of accessibility closely aligned with equality and self-investment. Innovation and creativity are discursively constituted as attributes that can be developed through specific, prescribed practices. These features appear to be associated with the economic values and principles of neo(new)-liberalism (p. 291)

It is noteworthy that four out of five articles that adopted such critical stances were published in Cultural Studies of Science Education, which in turn suggests that there are limited opportunities for such critiques and "ideological expansion" (Philip et al., 2018, p. 3) of STEM education in other journals. The dialogic nature in critical stance to NGSS within Cultural Studies of Science Education is evident in the following excerpt, in which Zouda (2018) presents an argument by building on the work by Zeidler (2016):

> The apparent inability of current STEM education to prepare citizens for life is also a main concern for Dana Zeidler (2016), who points to problematic issues in how STEM is presented in different U.S. policy literature, such as the Next Generation Science Standards (NGSS, 2013). He raises questions about what is omitted, mistreated and/or superficially presented in STEM education (p. 2).

What these authors are arguing against is the prescribed nature of measurable practices described in NGSS. They are also concerned about what is left out or absent in images of STEM education as depicted by NGSS.

Without the nuanced and critical discussions about the standardization that can result from unproblematic adoption or implementation of NGSS, researchers risk treating disciplinary knowledge as static and ontologically rigid. For example, Nugent et al. (2015) focused on problem solving as explained in the following way:

> While there are numerous learning strategies discussed in the literature, this research focused specifically on student problem-solving strategies, which has long been a critical focus of STEM education and is one of the criteria for the designation of a 'core idea' in the US Next Generation Science Standards (p. 1073).

In this study, problem solving was measured by pre- and post- multiple-choice assessments that covered "STEM content within the context of educational robotics activities" (p. 1074). The underlying assumption here is that STEM knowledge can be decontextualized and robotics design activities can be reduced to another instructional context for teaching more than one discipline (in this case, mathematics and computer programming), and not necessarily in an integrated manner. Thus, neither computer programming nor mathematical reasoning looks different from traditional contexts, and what counts as disciplinary knowledge in an un-integrated context remains unchanged in this study. This is an image of a linear addition of disciplines and stands in contrast to emergent images of disciplinary integration in science labs, which shows that integration across disciplines often results in new forms of representational and epistemic practices that advance each of the constituent disciplines (MacLeod & Nersesian, 2016).

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STEM Choices and Prevalence of Pipeline Metaphor

The most prevalent research topic (i.e., the focus of inquiry) in the current database was what we grouped as "STEM choices." This cluster of studies on STEM choices (n=34 or 23.7%) focused on whether high school or undergraduate students are choosing to study in a STEM discipline or whether students are aspiring for STEM-related careers. Studies tend to focus on specific student attributes (e.g., gender, race, socioeconomic status) and discuss the relationship between those attributes and their prospect of choosing STEM disciplines in postsecondary education or career. These studies reported interesting findings. On the one hand, male students were more likely to aspire STEM related disciplines or careers than female students (e.g., Chachashvili-Bolotin, Milner-Bolotin, & Lissitsa, 2016; Fredricks, Hofkens, Wang, Mortenson, & Scott, 2017; Lee, 2015; Sadler et al., 2012). On the other hand, some studies also reported that gender was not the most salient factor for students' choices (e.g., Adamuti-Trache & Sweet, 2014; Cerinsek et al., 2013; Maltese & Tai, 2011). Similarly, while some studies reported a racial gap in terms of White students persisting in STEM careers and disciplines compared to students of color (e.g., Andersen & Ward, 2014; Wang, 2013), other studies also reported no racial gap in STEM choice patterns (e.g., Lee, 2015; Maltese & Tai, 2011).

Several studies within the cluster of "STEM choices" also focused on program characteristics that enhance STEM-related career interests or postsecondary education for underrepresented youth (e.g., Means et al., 2017). Another set of studies examined how experiences of historically underrepresented students affect their choices to pursue STEM disciplines. A longitudinal ethnographic study conducted by Allen and Eisenhart (2017) depicted how racial minority high school girls fought back the common narratives to define them as deficits differently in two schools of different equity focus. McGee and Bentley (2017) adopted an anti-deficit perspective and highlighted the voices of successful Black women majoring in STEM disciplines and highlighted their resilience in manoeuvring systemic racism and sexism.

Within the cluster of "STEM choice," we also noticed that the metaphors of pipeline or pathway were frequently used in the studies in order to depict the connection among secondary education, postsecondary education and STEM-related careers. These metaphors are directly derived from the NGSS, which was widely cited in the current database of STEM education research, as mentioned before. The NGSS Lead States (2013) states:

> The United States has a leaky K-12 science, technology, engineering, and mathematics (STEM) talent pipeline, with too few students entering STEM majors and careers at every level from those with relevant postsecondary certificates to Ph.Ds. We need new Science standards that stimulate and build interest in STEM (p. xv).

Using critical discourse analysis focusing on metaphorical analysis, nominalization, and causal relationship (Fairclough, 2003), we further problematize what and where the metaphor of pipeline or pathway orients us toward. Except for Cannady, Greenwald, and Harris (2014), researchers who used the pipeline metaphor positioned it unproblematically (Adamuti-Trache & Sweet, 2014; Andersen & Ward, 2014; Maltese, Melki, & Wiebke, 2014; Sadler et al., 2017; Sahin et al., 2017). These studies assume and/or define the overarching goal of STEM education in terms of preparing students to join "the STEM pipeline." For example, Adamuti-Trache and Sweet (2014) framed their study on ethnicity and gender differences in students' STEM-related course selection, as follows: "It is not surprising that governments, policymakers and educators worldwide express concerns with the STEM educational pipeline" (p. 611). Andersen and Ward's (2014) study set up variables for "STEM pipeline status" (p. 224) and identified factors that could affect students' persistence. In reviewing the literature, Maltese et al. (2014) coined the issue of students' losing interest in STEM as "the leaky pipeline" phenomenon:

> Many students lose interest in STEM (the "leaky pipeline" phenomenon), and by the time students are ready to go to college only a small percentage actually pursue a degree that will lead to a future STEM career (p. 938).

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Alternatively, Cannady et al. (2014) suggested the use of "paths" instead of "pipelines." They argued that "paths are generally understood to be less rigid than pipes and 'going off the beaten path' has far more positive interpretations than the pipeline counterpart of 'leaking into the drain'" (p. 456). Along similar lines, Falk et al. (2016) used the phrase "STEM interest pathways." Their design-based research study focused on how contextual factors can create a wider STEM interest pathway. However, the inertia of the STEM pipeline metaphor was still present in the authors' conceptualization of the pathway, as evident in their conceptualization of pathways leading to careers in STEM: "Clearly, declining numbers of youth pursuing further STEM education and careers translates into fewer STEM professionals, leading to negative economic effects related to a lack of qualified workers available to fill the increasing number of STEM-related jobs" (Falk et al., 2016, p. 202).

In our current database, the most frequently used theoretical framework was sociocultural theory (n= 23). For this reason, we decided to closely examine the articles that employ sociocultural theory as their framing and also used the metaphor of "pathway" or "pipeline" in STEM education (n=3). Two of these articles simply mention "pathway" or "pipeline" but did not situate the learning activities and practices that students were engaged in as contributing to them joining the pipeline of STEM pathway. Here we focus our critique on only one article that situated the practice under investigation (i.e., gaming) as central to helping learners join the pathway or pipeline. Sociocultural theory of learning, based on Vygotsky's theory, emphasizes a dialectical unity of learning and development that is situated within and occurs across multiple histories (Vygotsky, 1978). It emphasizes learning as shifts in participation in communities of practices and "comprehensive understanding involving the whole person" (Lave & Wenger, 1991, p. 33). We focused on whether and how this commonly-used theoretical framing was in contact with the metaphor of "pipeline" or "pathway" in STEM education. For instance, Bricker and Bell (2012) argued "the incorporation of video and other gaming practices in STEM education is ripe with possibility with respect to STEM learning" (p. 899). Focusing on a single learner, they presented an examination of the participant's gaming ecology with respect to its sociocultural, historical, and material characteristics and affordances in order to understand how youth can develop considerable gaming expertise in informal settings. They also positioned such informal engagement with and expertise in games as potentially supportive for future STEM careers. However, it is also noteworthy that the video game in question is Halo 2, which is a first-person shooter game that has been critiqued in terms of its violent, racist and sexist representations (Nakamura, 2012). Using Halo 2 as a proxy for everyday gaming interests has also been critiqued as an assumption that foregrounds White masculine perspectives (Ong & Tzuo, 2011; Ortiz, 2019).

In other words, while the broader cultural context of our everyday lives was certainly being investigated here as relevant to learners' interests in STEM education, ideological explorations in the sense that Philip et al. (2018) argued for, was absent in these studies. Furthermore, even informal engagement with video games was positioned as a vehicle to help learners enter the STEM pipeline. This suggests that simply positioning studies as grounded in sociocultural theories of learning does not necessarily imply an orientation toward social justice, or even adopting a critical stance that can question the pipeline metaphor, as they might leave out considerations about ideological and critical theoretical positionings necessary for such orientations.

Summary and Discussion

Overall, we have illustrated how "STEM education" has been construed as a field of research in the decade of its early formation, focusing on the period between 2007 and early 2018. By intentionally limiting our search to the keywords that include STEM (i.e., STEM education, STEM learning, STEM reforms), our goal was to interpretively portray the current discourse around how "STEM" has been positioned in the context of STEM education research. In presenting the

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rich tapestry of this discourse, we have attempted to illustrate what counts as acceptable, what is implied and what counts as unsayable (Foucault, 1972; 1991) in STEM education. Grounded in our own perspective that positions critical transdisciplinarity as central to STEM education research, we adopted the tools of critical discourse analysis (Fairclough, 2003; Hall, 1992). Our analysis reveals how STEM education research represents the relationships between disciplines, as well as the macrosystemic discourses and ideological forces that have shaped what learning is and who the learners are (in the context of STEM education), especially during the period of early formation of the field. Our review surfaced several ways in which STEM education research has perpetuated disciplinary and geo-political hegemonies, either explicitly or implicitly. For example, our review of international journals depicted Americo-centrism in terms of the policy-level influences (e.g., NGSS) on the research literature in STEM education. The geopolitical matrix is interweaved ideologically through an underlying link between nationalist and militaristic ideologies and STEM education, as evidenced in conversations among engineering students depicted in Philip et al. (2018), as well as in the critical discourse analysis we presented. While policy documents explicitly position success in STEM education as central to issues of global competition and national security, these links are often present implicitly in the form of highly prevalent nominalized metaphors such as the STEM pipeline and the STEM pathway(s), which in turn are positioned as the underlying motivation for K-16 STEM education. Fairclough (2003) pointed out that the effect of nominalization is its power to conceal the agents of action — the subjects and objects of the action — and to discursively construct an independent entity. In our case, nominalization masks some of the key questions such as: Who are the subjects created by STEM pipelines? Where are STEM pipelines orienting us toward?

Instead of answering or even asking these questions, many research articles we reviewed oriented us toward the discourse of human capital, but without examining how intricately the notion of human capital is tied to ideological forces of economic growth and global competitiveness. Only a handful of articles in our review adopted a critical stance and alerted us to such discourse through their analyses of policy documents and curricula (e.g., Garibay, 2015; Hoeg & Bencze, 2017a, 2017b; Storksdieck, 2016; Zeidler, 2016; Zouda, 2018). According to Sen (1997), human capital focuses on "skill and knowledge as well as effort — in augmenting production possibilities" (p. 1959). In contrast, the concept of human capabilities underlines the significance of "the ability of human beings to lead lives they have reason to value and to enhance the substantive choices they have" (Sen, 1997, p. 1959). Sen does not deny the fact that economic growth can lead to the expansion of human freedom to choose the kind of lives they want to live. However, as is often the case, arguments around human capital tend to concentrate on productivity and economic growth and do not extend the discussion to "why economic growth is sought in the first place" (Sen, 1997, p. 1960). Emphasizing that human beings are not merely means of economic production, Sen (1999) reorients human capital discourse to human capability that could bring about social change beyond economic growth.

Positioning STEM education in light of critical transdisciplinarity is a way forward for countering instrumentalism and narrowly defined ideological forces that emphasize human capital. Our review shows that, left unchallenged and unquestioned, capitalist, nationalist and militaristic ideologies can co-opt and orient STEM education toward instrumentalist (Higgins, 2008) rather than aesthetic purposes (Dewey, 1934; Farris & Sengupta, 2016). An aesthetic education can help us see more rather than merely seeing as (Higgins, 2008). The distinction here is between a rudimentary form of recognition (seeing as), as opposed to experiencing the richness and complexity of the situation at hand (seeing more). Seeing more can reveal the "the thorny, the surprising, the complex" (Higgins, 2008, p. 14), whereas seeing as becomes a case of arrested perception. In absence of an aesthetic vision, preparation of a STEM workforce then becomes the overarching goal for STEM education, and the emphasis shifts away from a truly democratic vision of education. In contrast, as Sengupta et al. (2019) argued, in an aesthetic imagination, experiencing the thorny, the surprising, and the complex should involve seeing more critically and historically, echoing similar calls issued by Philip et al. (2018).

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Our analysis also reveals how bodies of learners are conceptualized in both tacit and explicit ways. As observed in many studies in our review, bodies of learners were often reduced to sets of attributes or variables (e.g., gender, race, ethnicity, and socioeconomic status) that shape learning. The risk of reducing our intersectional histories and experiences to deterministic categories is the further subjugation of learners and erasure of the heterogeneity of their histories, desires and experiences by disciplinary apparatus. As Puar (2005) poignantly noted: "difference is encased within a structural container that simply wishes the messiness of identity into a formulaic grid" (p. 128). A case to point is that in our current database, no study focused on disabled bodies or queer bodies and their experiences in STEM education. In aesthetic imaginations of our bodies and histories, silenced forms of embodied mathematical cultures, learnt intergenerationally, can offer new transdisciplinary contexts and representations (Takeuchi, 2018). Experiences of gender- and sexuality-based marginalization and resilience could also offer phenomena, contexts and narratives for fundamentally re-orienting STEM education toward who learners become, rather than merely focusing on what to learn (Paré, Sengupta, Windsor, Craig, & Thompson, 2019; Paré, Shanahan & Sengupta, in press).

It is also important to note that due to the exclusive focus on English-medium publications, our article does not provide a complete picture of STEM education. It leaves out reforms, policies and practices that are happening beyond English-speaking countries. Our focus on science and mathematics education journals also exclude, for example, engineering education journals, where conversations around STEM education are now beginning to take shape. In addition, the focus on transdisciplinarity could also be evident in the works that do not use the term "STEM education" (e.g., the vast body of research on children's long-term development in science and mathematics education by Lehrer & Schuable, 2000) that we have not focused on this article.

Despite these limitations, by intentionally delimiting our research, we were able to provide a rich illustration of key discourse that characterizes the disciplinary hegemony in the field of STEM education in the decade of early formation, especially in widely-circulated and widely-read English-medium journals. Our review adds to existing literature reviews on STEM education (e.g., Belland et al., 2017; Kim et al., 2018; Reinhold et al., 2018), by centralizing the questions anchored in the notion of transdisciplinarity: how can we mobilize discipline more toward epistemological and ontological liberation? In this light, our review amplifies the current collective efforts to push the boundary of STEM education toward a more critical and emancipatory transdiscipline (McKinney de Royston & Sengupta-Irving, 2019; Sengupta et al., 2019; Vakil & Ayers, 2019).

Implications for STEM Education Research

Overall, our review suggests that although going beyond a single discipline and "real-world" complexity are often cited as motivations behind STEM integration, research efforts typically lack a deep engagement with critical transdisciplinarity. To this end, we believe that the following calls to action can offer productive re-orientations for STEM education researchers.

1. Reorient the research foci away from human capital discourse

Our Findings suggested that approximately 40% of the studies focused on students' interests in pursuit of STEM-related careers. The meaning and experiences of STEM education for learners in such studies are thus reduced to the enhancement of human capital. More studies on what learners are actually learning and what the experiences of STEM learning for learners are needed, in order to reorient the current discourse of STEM education in a way that foregrounds the phenomenology of learning and teaching in transdisciplinary contexts (e.g., Vossoughi, Hooper & Escudé, 2017; Sengupta et al., 2019). Such studies can shed light on the meaning of STEM learning even for students who choose not to pursue postsecondary education

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in STEM education, and inch us closer to a more democratic imagination of STEM education. Furthermore, as evident in our analysis, the outcome-oriented focus also does not include young learners and the elderly and disabled bodies, for example. As we begin to include a more diverse group of people (beyond the limited scope of normatively defined secondary and postsecondary students) as learners and participants in STEM discourse, both within and across formal and informal settings and across the lifespan, we can also begin to develop a richer understanding of transdisciplinarity in STEM education.

2. Envisage disciplinary and spatial expansions of STEM education research

In defining transdisciplinarity, we emphasized the liberation of discipline to relinquish geo-political constraints and expand epistemological boundaries. As our findings suggest, most STEM education research is conducted in the context of the United States. By going beyond the geo-political boundaries of the US and the ideology of US nationalism and militarism, we also call upon for broadening our epistemological and ontological frameworks — not merely the research contexts — in ways that bring into play perspectives from the global South.

We also identified the overreliance on science education defining and situating what should count as STEM education. In our current database, STEM education was mostly defined by the disciplinary practices and languages within sciences or science education. The use of certain technologies such as computational modelling and robotics, and the allusion to "design" mostly defined interdisciplinarity in STEM education. However, the notion of design was rarely (if at all) explored beyond the notion of iterative improvement. By limiting the inclusion of other disciplines such as mathematics, arts, media studies, humanities, social studies and the law and so forth, our imagination of design and STEM education can be severely constrained. We therefore call for the inclusion of people, knowledge, and practices in defining STEM learning, beyond the disciplinary hegemony of science.

3. Focus on emergence generated from transdisciplinarity

We argued that critical transdisciplinarity stands against individualization of multiplicities, in a sense similar to Foucault's (1977/2007) problematization of the singularity of "discipline." We defined transdisciplinarity as going beyond amalgamation of two or more disciplines, to include the synergistic and reflexive relationship achieved through dialogues among people, practices, and constructs from multiple disciplines. What results from such conversations is an emergent phenomenon, in the sense that the whole is greater than the sum of the parts and that disrupts and challenges the disciplinary hegemony. When multiple disciplines are integrated in practice with one another, what results are new representational and epistemic practices that advance each of the constituent disciplines (MacLeod & Nersesian, 2016). Standardizing STEM learning, on the contrary, can inhibit transdisciplinary inquiries and instead orient us toward reproducing disciplinary hegemonies. Such reduction of disciplinary practices contrasts with the image of scientific practice Pickering (1995) depicted as the "mangle of practice" — "the reciprocal tuning of human and material agency" (p. 21). The image of STEM education as a boundary object (Shanahan et al., 2016) invites us to engage in boundary play with disciplinary formations (Sengupta & Shanahan, 2017). In contrast, the rigidity of standardization without adequate attention to the role of uncertainty (Duschl, 2008) and heterogeneity (Rosebery et al., 2010; Sengupta et al., in press) can counter emergent disciplinary excursions (Azevedo, 2013) that in turn can radically expand our imagination of STEM education.

In a more critical sense, we also positioned queering disciplines at the core of emergence — questioning, mobilizing, and unsettling with the settledness within and across disciplines (Ahmed, 2006). This is an invitation to continue deepening disciplinary practices while also

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bringing to light learners' bodies, histories and desires, especially in contexts where they have been historically marginalized. Such forms of critical and transdisciplinary engagement can radically alter the representational infrastructure that we take for granted in STEM education, and also offer ideological expansions of what can and should count as disciplinary authenticity (Lam-Herrera et al., 2019; Philip et al., 2018; Takeuchi & Dadkhahfard, 2019). It is toward such greater imaginations of critical transdisciplinarity that STEM education can orient us, rather than restricting us to instrumentalist and nationalist discourses and ideological forces.

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Appendix: The List of Journals Selected for Close Review

- American Educational Research Journal
- Computers and Education
- Journal of Research in Science Teaching
- Learning and Instruction
- Cognition and Instruction
- Cultural Studies of Science Education
- Educational Studies in Mathematics
- For the Learning of Mathematics
- Harvard Educational Review
- International Journal of Computer-Supported Collaborative Learning
- International Journal of Science Education
- Journal for Research in Mathematics Education
- Journal of Mathematical Behavior
- Journal of Mathematics Teacher Education
- Journal of Science Teacher Education
- Journal of the Learning Sciences
- Mathematical Thinking and Learning
- Mind, Culture, Activity
- Science Education
- Studies in Science Education
- ZDM: Mathematics Education
- International Journal of STEM Education

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