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STUDENT ENGAGEMENT IN SCIENCE AND USER-CENTERED ENGINEERING: EDUCATIONAL DESIGNS WITH YOUNG ADOLESCENTS IN AN INVENTION CAMP AND CLASSROOM UNIT

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Abstract

Student Engagement in Science and User-Centered Engineering:

Educational Designs with Young Adolescents in an Invention Camp and Classroom Unit

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Student engagement is a central concept for educational practitioners, researchers, and evaluators, both as its own outcome and as connected with motivation, achievement, attainment, careers, and civic participation. In science and engineering education, young adolescence is a period when many students become disaffected or disengaged, especially when youths’ racial and ethnic, cultural and linguistic, and gender identities are not sustained through educational designs and implementations. Since a reemergence in the 1980’s, scholarship has approached student engagement in either individualistic or collectivist ways, with more hybrid and holistic models only recently emerging. In particular, more work is needed to explore whether *social engagement* is its own distinct dimension, or whether it intersects with dimensions like *affective*, *behavioral*, and *cognitive* engagement.

This three-paper dissertation takes a philosophical lens of dialectical pluralism to interrelate multiple worldviews when examining student engagement, during an in-school-time invention project and an out-of-school-time invention camp. Adopting the methodology of a cultural psychology approach to design-based research, the study first

considers the project and camp separately, then culminates in a cross-case comparison of the two. All papers are situated in “Mills City Public Schools”, a semi-urban district in the Northeast US.

The first paper considers the second iteration of an insulating-device project with grade seven students. The second paper explores the second annual “Winter Vacation Camp” with grades six-eight campers inventing electronic doors. The third paper compares those two interventions, in a manner targeted towards educational practitioners. In sum, the paper-set provides qualitative, quantitative, and integrated evidence that a six-dimensional model is conceptually warranted and practically useful, through examples at the individual, small-group, and classroom/camp levels. Further, it provides educational design considerations for both in- and out-of-school time learning environments. The new model and design considerations support planning and analysis for more equitable engagement of youth, especially those with identities historically minoritized in science and engineering education.

Dedication

This work is dedicated to young adolescents, each and all, whose ascending (from Latin *adolescere*) generates hope and resistance as societies work to humanize each and all members; and to those who work and learn with young adolescents.

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Section I: Introduction to the Three-Paper Set

Rationale and Research Questions

What is engagement? Studied for at least hundreds of years, engagement of students in schools experienced a rebirth of interest in the 1980's amidst school-dropout studies (Christenson et al., 2012; National Research Council and the Institute of Medicine, 2004). Initially confined to more behavioral conceptions such as attendance, disciplinary action, and grades, student engagement has since broadened in affective/emotional, cognitive, and social dimensions (Fredricks, Wang, et al., 2016). Its relevance has accordingly broadened amongst practitioners, researchers, and evaluators, both as an outcome itself and as a mediator, moderator, or predictor linked to shorter- and longer-term academic, socioemotional, career, and civic outcomes (J. Bell, Besley, et al., 2019; Christenson et al., 2012; Fredricks, Filsecker, et al., 2016; Järvelä & Renninger, 2014).

In science and engineering education, young adolescence is an especially sensitive period for youth becoming engaged or disengaged/disaffected. Students from historically minoritized backgrounds in particular, such as students of color and/or girls and gender non-binary students, can be discouraged from science and engineering experiences that are culturally irrelevant or even destructive (Tytler & Osborne, 2012). Some studies of student engagement attend to more collectivist phenomena, while others focus on more individualistic concerns (Olitsky & Milne, 2012). An emerging line of research in need of more attention includes studies that attend to both collectivist *and* individualistic dynamics (Fredricks, Filsecker, et al., 2016).

The present study adds additional evidence, nuance, and extension to extant models of student engagement, contributing insight to individual|social dialectics, especially with respect to affective engagement. Through two curriculum interventions of user- and activity-centered design, this three-paper set uses an in-school-time class, an out-of-school-time camp, and a cross-case comparison thereof to suggest ways that researchers and practitioners can design for student engagement in science and engineering activities. It builds on more conceptual work for student engagement in general, as well as more empirical work on science and engineering in particular, to promote more equitably engaging learning environments for all young adolescents. The three papers address the Research Questions listed in Table 1.1.

Positionality Statement

Before discussing the conceptual framework through which I approach this study, I will make explicit my positionality in this work. I am a white, heterosexual, cisgendered male, from an upper-middle-class background. I am a native speaker of American Dominant English, born in the United States (US). As such, I approach research with extensive, unearned privilege, that often comes with obliviousness and fragility, for which I must constantly challenge myself and seek to build resilience (DiAngelo, 2011; McIntosh, 1988, 1992; Saad, 2018). Coming from various privileged groups (Goodman, 2011), and intersectionalities thereof (Cho et al., 2013), I have to behave as an ally – if

Table 1.1

Research Questions for the Overall Dissertation and the Three Papers

Overall	What are some educational design considerations for promoting affective and social engagement, alongside development of self-efficacy, with young adolescents in practices of science and user-centered engineering?
Paper 1	1.1) During a **7th grade invention project**, how did youth affectively and socially engage in practices of **science, engineering, and inventing**? 1.2) How did engagement in practices support **students'** development of self-efficacy? 1.3) Which educational design considerations interacted with **students'** engagement and practices?
Paper 2	2.1) During a **grades 6-8 invention camp**, how did youth affectively and socially engage in practices of **inventing**? 2.2) How did engagement in practices support **campers'** development of self-efficacy? 2.3) Which educational design considerations interacted with **campers'** engagement and practices?
Paper 3	3.1) Which educational design considerations support middle-school youths' engagement, practices, and self-efficacy in design-focused **camps and classes**? 3.2) Which design considerations are ***separate*** for in-school-time and out-of-school-time (IST and OST)? 3.3) Which design considerations are ***shared*** for IST and OST?

not an accomplice or co-conspirator – working *with* persons from minoritized groups, rather than as a savior doing research *on* them (Pollock, 2008; Saad, 2018). My interest in working with young adolescents has developed over 17-plus years working in US middle schools (two years during the school day, two years in a Master's program, eight more years during the school day, and now five-plus years in a Ph.D. program – with out-of-school time work throughout). Working in a variety of urban, suburban, and semi-urban settings, I see student engagement in education as a vehicle for building connections and understanding across identity markers that all too often lead to segregation and ignorance (e.g., race and ethnicity, gender, socioeconomic class, national origin; Cho et al., 2013).

My work in student engagement and disciplinary practices is influenced by a philosophy of *critical dialectical pluralism* (Onwuegbuzie & Frels, 2013) and a *cultural psychology* approach to design-based research (P. Bell, 2004). For example, my mixed methods project is imbued with constructivist, postpositivist, pragmatist, and transformative worldviews (Creswell & Plano Clark, 2018) at the very least, and my preferred "unit" of analysis is a dialectic between individual and social considerations (e.g., individual students and cooperative teams). Accordingly, rather than seek philosophical/theoretical harmony of one worldview across all elements of the study, I explicitly embrace the plurality between and within all stakeholders of the project – including myself – in ways that emphasize the aspirations and resilience of populations historically minoritized in science and engineering.

Conceptual Framework for the Dissertation as a Whole

This study is anchored in student engagement theory, which, from its foundations in school-dropout prevention, has flourished in increasingly holistic ways amongst many research approaches, involving learners of all grade levels (Christenson et al., 2012; Eccles, 2016). Given that student engagement tends to be situated in specific disciplines (Fredricks, Filsecker, et al., 2016), in the current study I situate student engagement in practices of science and engineering (NGSS Lead States, 2013a; Rodriguez, 2015) as well as activity- and user-centered design (Norman, 2005).

Student Engagement, as Theory

Student engagement theory is a term mostly reserved for grades 13-20 education (Astin, 1984; Pike & Kuh, 2005); researchers in pK-12 settings tend to consider student engagement to be a concept related to theories of motivation (Boekaerts, 2016; Eccles, 2016). In my framework, I consider student engagement *as* theory due to it being more specific than a worldview, plus given its utility as an *inductive interpretive approach*, wherein theory can serve as a preliminary framework to be modified per data analysis (Creswell & Plano Clark, 2018). This approach has been employed by Fredricks and colleagues, as they moved from a three-dimension model (Fredricks et al., 2004) to a four-or-six-dimension model (Fredricks, Wang, et al., 2016). The three-dimension model of *behavioral, cognitive,* and *affective* (or *emotional*) engagement was immensely popular with researchers for over a decade (Christenson et al., 2012). More recently, a dimension of *social* engagement has emerged, related to cooperating or collaborating with classmates and teachers; however, it is unclear as to whether it is a separate and fourth dimension, or whether it might create a six-dimensional framework (i.e., individual-behavioral, individual-cognitive, individual-affective, social-behavioral, social-cognitive, and social-affective; Fredricks, Wang, et al., 2016).

Practices of Science and User-Centered Engineering

The Next Generation Science Standards (NGSS; NGSS Lead States, 2013a), represent a shift towards practice-based learning in science and engineering. The NGSS posit that engaging in a practice "requires not only skill but also knowledge that is specific to that practice" (NGSS Lead States, 2013b, p. xv), moving beyond previous instructional models that emphasized memorization of isolated knowledge or decontextualized performance of skills. The NGSS include eight Science and Engineering Practices (SEPs), six of which are identical for science and engineering, and two of which only slightly differ: (1) Asking questions (for science) and defining problems (for engineering); (2) Developing and using models; (3) Planning and carrying out investigations; (4) Analyzing and interpreting data; (5) Using mathematics and computational thinking; (6) Constructing explanations (for science) and designing solutions (for engineering); (7) Engaging in argument from evidence; and (8) Obtaining, evaluating, and communicating information (NGSS Lead States, 2013c, p. 48). For the present study, using the NGSS to define science and engineering practices is an appropriate choice, as the participating district has spent the past nine years aligning to the NGSS and closely-related state standards.

Practices of Activity- and User-Centered Design

Practices of design can be broadly grouped in terms of *user-centered design*, *activity-centered design*, or neither (Dearden et al., 2008; Mackenzie, 2002; Norman, 2005). For the context of this study, tensions exist between frameworks, standards, curriculum, instruction, and analysis, as will be detailed in the Methods sections. For now, design will be approached in ascending order of scale, following the *ecological systems of development* model by Bronfenbrenner (1993). I begin with design that sometimes centers on an individual level, namely user-centered design.

The “user” in user-centered design could be an individual person, a more-than-human entity (e.g., a dog), or some social group (e.g., a research-practice partnership).

Regardless of scale, user-centered design tends to focus on adapting technology to the user (Norman, 2005). In principle, the intended user is involved with much-if-not-all of the development process, though in practice user involvement can be inconsistent or even counter-productive (Dearden et al., 2008; Norman, 2005; Vredenburg et al., 2002). Often the intended user is a real or hypothetical person or category of person, as in *human-centered design*; however, at times "human-centered design" might be a misnomer, as some enactments focus on groups (Dearden et al., 2008; IDEO.org, 2015; Norman, 2005, 2013). Further, some approaches broaden the nomenclature of "user" as *culturally-centered*, *-focused*, or *-oriented* design (Gaver et al., 1999; Röse, 2004; Vigil-Hayes et al., 2019; Watkins & Barnes, 2010; Whitney & Kumar, 2003) or *community-based design* (Hutter et al., 2011). While these approaches still tend to have individual users as their ultimate clients, they inherently involve broader questions of social identity markers such as language, race and ethnicity, culture, national origin, gender, and socioeconomic class. However, they sometimes stop short of intersectional approaches that could more explicitly address issues of domination and marginalization according to said identity markers (Cho et al., 2013; Costanza-Chock, 2018; Gunckel & Tolbert, 2018).

Activity-centered design, sometimes called *performance-centered design*, offers some potential advantages over user-centered design (Dearden et al., 2008; Gunckel & Tolbert, 2018; Mackenzie, 2002; Norman, 2005). First, activity-centered design holds promise to be more adaptable to a diverse audience of users, who themselves are changing over time. Second, an activity-centered approach can mitigate potential negative effects of one user upon other users or unintended stakeholders. Finally, an activity-centered approach might result in more compromise and flexibility, rather than a an overly complex solution that attempts to address extensive feedback from a smaller number of users per a user-centered approach.

Design in Frameworks and Standards

In general, design is flexibly defined as activity- or user-centered in the NGSS and in the document upon which the NGSS are based, *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (*Framework*; National Research Council, 2012).

For the SEP of constructing explanations (for science) and designing solutions (for engineering), the *Framework* states that

> [engineering design] elements consist of specifying constraints and criteria for desired qualities of the solution, developing a design plan, producing and testing models or prototypes, selecting among alternative design features to optimize the achievement of design criteria, and refining ideas based on the performance of a prototype or simulation. (p. 69)

The *Framework* positions engineering as seeking “solutions to particular human problems” (p. 11), such as “a traffic pattern for the school parking lot” (p. 70), resulting in technology that will “satisfy human needs and wants” (p. 12). In discussing the nature of engineering (and science), the *Framework* states that “science and engineering…are human endeavors”, with “historical, social, cultural, and ethical aspects” (p. 248). However, the *Framework* intentionally avoids elaborating these aspects “at the level of framework and standards", arguing that those matters would be "better treated at the level of curriculum design" (p. 248).

Ultimately, most scholars concur that design is an inherently interdisciplinary process, involving stakeholders like scientists, engineers, artists, economists, technologists, marketers, distributors, retailers, customer support representatives, and users (Norman, 2013). While some design can provide tremendous benefits to individual users at distinct moments in time, extra care is needed to minimize or eliminate negative effects beyond the intended user(s), as cultural and social contexts can change in the future, especially for minoritized individuals and populations (Costanza-Chock, 2018; Gunckel & Tolbert, 2018; Norman, 2005).

Self-Efficacy Theory

Situated within the broader field of social cognitive theory, self-efficacy theory examines an individual's or group's "belief in their ability to produce given attainments" (Bandura, 2006, p. 307). Through the lens of a "triadic reciprocal" relationship, self-efficacy focuses on personal, environmental, and behavioral(/interactional) factors (Bandura, 2001, p. 14). Self-efficacy can arise from sources across four dimensions, including *performance accomplishments*, *vicarious experience*, *verbal persuasion*, and *emotional arousal* (Bandura, 1977). For example (respectively), a student may develop self-efficacy through winning an invention contest or by demystifying invention through participation in a project; through observing an invention process in live or recorded formats; through being told by others *or by themselves* that they did well during an invention project; and through developing confidence or lessening anxiety via exposure to inventing. Regardless of their source(s), self-efficacy expectations vary in their *magnitude* (towards overcoming difficulty of tasks), *generality* (across situations), and *strength* (amidst disconfirming evidence) (Bandura, 1977).

When applied to cognitive development, including various academic and social-emotional forms of learning, self-efficacy is expressed through (meta-)*cognitive*, *affective*, *motivational*, and *selection* processes (Bandura, 1993). For example (respectively), self-efficacy may affect a student's or team's beliefs about their invention ability, their competence relative to peers, the usefulness of feedback, and the controllability of their learning environment; self-efficacy can influence the ambitiousness of a student's or team's goals for the project, their reactive responses to actual challenges, and their pro-active efforts towards potential challenges; self-efficacy can mitigate negative self-talk, anxiety, or even depression after a disappointing event, project, or year; and self-efficacy can support opting-in to future invention classes, clubs, camps, courses of study, hobbies, and careers.

In general, student engagement and self-efficacy are mutually constructive or destructive; a learner or group with large, broad, and strong self-efficacy is more apt to become and remain engaged, and vice versa (Schunk & Mullen, 2012). Though both student engagement and self-efficacy tend to be situated in specific disciplines, they differ in timescale, with student engagement usually studied on shorter timescales relative to self-efficacy (Christenson et al., 2012; Schunk & DiBenedetto, 2016; Schunk & Mullen, 2012; for a notable exception, see Lewenstein & Philips, 2019). In this paper set, student engagement is both a shorter-term outcome of its own interest, as well as a consideration for the longer-term outcome of self-efficacy.

Educational Design through the Social Infrastructure Framework

Consistent with individual|social dialectics for both student engagement and self-efficacy, the Social Infrastructure Framework by Bielaczyc (2006) foregrounds both individual and social aspects of educational design. The SIF includes 18 *design considerations* across four *dimensions*: *cultural beliefs*; *practices*; *socio-techno-spatial relations*; and *interaction with the "outside world"*. Grounded in the learning sciences (Yoon & Hmelo-Silver, 2017), the SIF was created "as both a design tool and an analytic tool within design research" (Bielaczyc, 2006, p. 325), useful across multiple iterations of a design-based project. One example relates to the design consideration of *the associated participation structures of students*. This consideration manifested in the initial design of *four* teammates for four roles, as well as the analysis suggesting that the roles might be better performed in groups of *three* teammates (i.e., thematic coding generated data in support of increased participation and flexibility in three-member teams). This framework promoted understanding the *cultural psychology* (P. Bell, 2004) at the classroom and camp levels, consistent with the methodology as described in the Abstract and Positionality Statement.

Overview of the Paper-Set

This paper-set proceeds chronologically with respect to the two interventions, acknowledging that the first intervention informed the second intervention (i.e., findings from the Fall 2018 in-school-time project informed the February 2019 out-of-school-time camp). The cross-case paper is presented third, due to it drawing upon and extending from the first two papers.

Section II – Paper #1, '"Energetic, but also relaxed": Self-efficacy via Social and Affective Engagement in a Grade-seven Insulating-device Project'

The first paper, targeted for the *Journal of Research in Science Teaching (JRST)*, builds upon student engagement as studied across a wide variety of timescales and grain sizes (e.g., seconds to years, and individual to societal). In addressing the individual|social dialectic of student engagement, the manuscript positions the former as smaller-scale and shorter-term, and the latter as moderate-scale and moderate-term. Seeking to bridge the differences in space-time, the paper provides evidence connecting individual and social approaches to affective, behavioral, and cognitive engagement. The paper describes examples of synergy between individual and social dimensions, such as being individually "energetic", "but also (socially) relaxed" ("Jay", post-interview). Other examples show individual and social dimensions in conflict, with personal insecurities being mitigated by peers' reassurances. The paper concludes by conjecturing some design considerations to leverage individual|social dialectics towards developing students' self-efficacy for inventing, mostly though ways to expand ideas about who is an "inventor" and what counts as evidence of "inventing".

Section III – Paper #2, "'Magic' or 'maybe ... other years': Designing for Young Adolescents' Engagement and Self-efficacy in an Invention Camp"

The second paper, for the *International Journal of Science Education, Part B: Science Communication and Public Engagement (IJSE-B)*, is situated in a less structured learning environment than the first, namely a one-week vacation camp. In reference to the paper's title, the reduced structure worked like "magic" for some campers (Pedro, post-interview), yet left other campers feeling like camp would be much better "maybe … other years" (Edith & Sara, post-interview). In the case of "magic", individual engagement was enhanced by social engagement, often implicitly; the converse was true for less supportive groups. Whereas the first paper's conjectures center on *expanding* educational design, this second paper suggests *focusing* participation to counteract socialized stereotypes, in particular with regard to gendered identities. The paper argues that designing for more balance of roles, yet explicitly promoting fluidity between roles, can promote self-efficacy for inventing.

Section IV – Paper #3, "Inventors Emerging In- and Out-of-School: Five Years of Adolescent Student Engagement in Classes and Camps"

The third paper is prepared for *Connected Science Learning (CSL)*, a practitioner-oriented journal that explicitly connects learning in-school-time and out-of-school-time (IST and OST). This paper synthesizes evidence from the first two papers, supporting a proposed six-dimensional model of student engagement (i.e., individual-affective, individual-behavioral, individual-cognitive, social-affective, social-behavioral, and social-cognitive). Further, the paper shows ways in which the two settings can inform each other, in general promoting more affective engagement IST and more cognitive engagement OST. Design conjectures are tailored for the practitioner audience, including readily actionable survey suggestions and numerous practical and freely-available references and resources.

Section V – Conclusion

The Conclusion begins with integrated findings across the three papers. Then, it describes the study's contributions to the fields of student engagement, self-efficacy theory, and educational design. Finally, it ends with future directions for scholarship.

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Section II (Paper #1), '"Energetic, but also relaxed": Social and Affective Engagement in a Grade-seven Insulating-device Project'

ABSTRACT

Student engagement interests practitioners, researchers, and policymakers, for practical uses as an outcome, predictor, mediator, and moderator, as well as conceptual applications to theories of motivation and self-determination. Both individual and social models of student engagement are common, yet scholarship has only begun to develop more holistic models. Team-based invention education has potential to promote engagement with an individual|social dialectic, for learning environments that build upon persons' cultural and linguistic assets in both cooperative and competitive ways. We extend understandings from out-of-school-time invention education, towards an in-school-time intervention with eight classes of grade-seven youth in a semi-urban public school of the Northeast US. Students worked in teams to design, build, and test shoebox-size insulating devices, drawing upon disciplines of science and user-centered engineering. Our design-based research approach highlights several *design considerations* through the Social Infrastructure Framework of Bielaczyc (2006), with connections to affective|social engagement as well as to students' self-efficacy for inventing. Using a mixed research design for convergence, we firstly found increases in self-efficacy through ability beliefs, in descending effect sizes for more science-, engineering-, and inventing-focused items, respectively. Secondly, there were decreases in self-efficacy through selection of future invention opportunities, in part affected by the examples of inventors in unaltered vs. altered curriculum (professional adults vs. amateur youth, respectively). And thirdly, we found no statistically significant changes in self-efficacy through anxiety management, as individual stressors were mitigated by social supports. We discuss implications for educational design, especially the structure of learning activities, the framing of learning and knowledge, and the social positioning of students. Concluding remarks address contributions to individual|social dialectic models of student engagement, along with finer-grained and more nuanced understandings of developing students' self-efficacy, particularly for technological inventing and other user-centered engineering.

Keywords: student engagement; self-efficacy; educational design; young adolescents; user-centered engineering

1 | Introduction

Student engagement is a central yet diffuse concept for educational practitioners, researchers, and evaluators. In its practical sense, it is an "everyday… term… among teachers" with an element of conceptual "slipperiness", including individual, social, and dialectic models (Olitsky & Milne, 2012, p. 20), for educational, institutional, and democratic purposes (Lewenstein & Philips, 2019). From a broad theoretical lens, student engagement is a concept linked to theories of self-determination, self-regulated learning, expectancy-value, and flow (Azevedo, 2015; Christenson et al., 2012; Eccles, 2016; Fredricks, Filsecker, et al., 2016). In evaluation, student engagement has served as predictor, outcome, mediator, and moderator amongst measurements related to student health, school persistence, academic achievement, teacher effectiveness, and peer influences (Christenson et al., 2012).

Student engagement is especially important in science education, particularly for youth from populations historically marginalized in science (Maltese & Tai, 2010, 2011; Olitsky & Milne, 2012; Tytler & Osborne, 2012; Wade-Jaimes & Schwartz, 2019). Early adolescence, roughly ages 10-15 (Santrock, 2007), is a crucial time for developing interest in science (Olitsky & Milne, 2012), which can persist throughout schooling and into careers (Maltese & Tai, 2011). However, science teaching is often practiced by educators with misaligned qualifications using lecture- and textbook-intensive methods (Tytler & Osborne, 2012), failing to provide the "energetic, yet relaxed" environment described by one participant in our study. Invention education, a specialized type of user-centered engineering (Invention Education Research Group, 2019), shows promise for engaging students in interdisciplinary ways, as they learn through science and engineering practices (NGSS Lead States, 2013; Rodriguez, 2015). To realize that promise, the current study took a *cultural psychology* approach of design-based research (P. Bell, 2004) to better understand dialectics between students' social and affective engagement in science class, with implications for both theory and practice. We were guided by the research questions,

1) During a 7th grade invention project, how did youth affectively and socially engage in practices of science and user-centered engineering?

2) How did engagement in practices support students' development of self-efficacy?

3) Which educational design considerations interacted with students' engagement and practices?

2 | Conceptual Framework

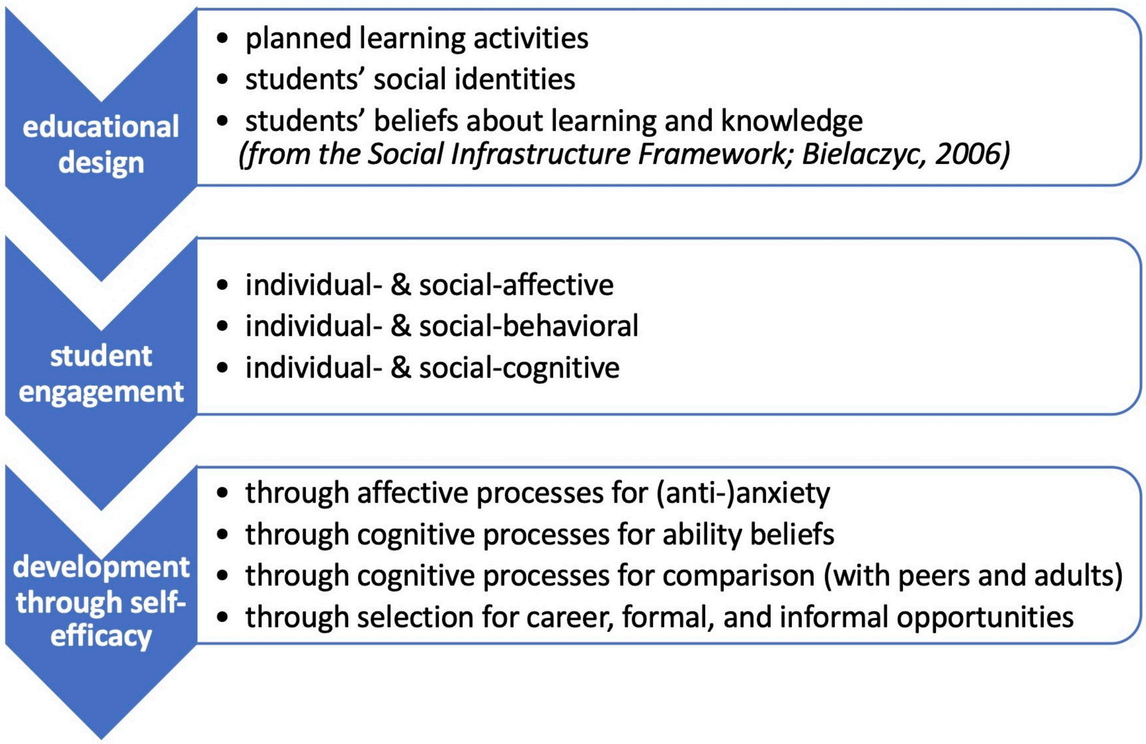
We approach learning as an individual|social dialectic, in a sociocultural manner consistent with a *cultural psychology* approach to design-based research (P. Bell, 2004). In this study, we examine processes and outcomes related to individual students and student-teams, as situated in their classrooms and broader communities (Bronfenbrenner, 1993). The processes on which we focus are educational design, student engagement, and development of self-efficacy. We detail these constructs in the following subsections and summarize our conceptual framework in Figure 2.1.

2.1 | Educational Design with the Social Infrastructure Framework

Created for both design and analysis of technology-based learning environments, the Social Infrastructure Framework, or SIF, by Bielaczyc (2006) makes explicit the sociocultural factors that sometimes remain tacit in educational design. The SIF includes 18 *design considerations* across four *dimensions* of educational design: *Cultural Beliefs*, *Practices*, *Socio-techno-spatial relations*, and *Interaction with the "outside world"*. In this paper, the core technology is an insulating device roughly the size of a shoebox. At the same time, we noted auxiliary technologies related to paper-, PDF-, and Google Docs-based versions of the student guidebook, as will be detailed in the Results section.

Figure 2.1

Synergies between Components of Conceptual Framework



For the present study, data analysis revealed that the most salient design considerations were *How learning and knowledge are conceptualized* and *How a student's social identity is understood* (both from the *Cultural beliefs* dimension) and *The planned learning activities* (from the *Practices* dimension). For instance, in terms of learning and knowledge, students and teachers varied in their emphases on epistemological goals, including values such as achievement (e.g., course grades), beneficence (for a given client or activity), completion (of required tasks), effectiveness (at minimizing temperature change), and efficiency (based on both effectiveness *and* cost). The manifestations of students' social identities included roles such as cooperator, competitor, and outsider. Examples of planned learning activities were scientific experiments, engineering design challenges, and invention-centric posters and mock-patent applications.

2.2 | Student Engagement

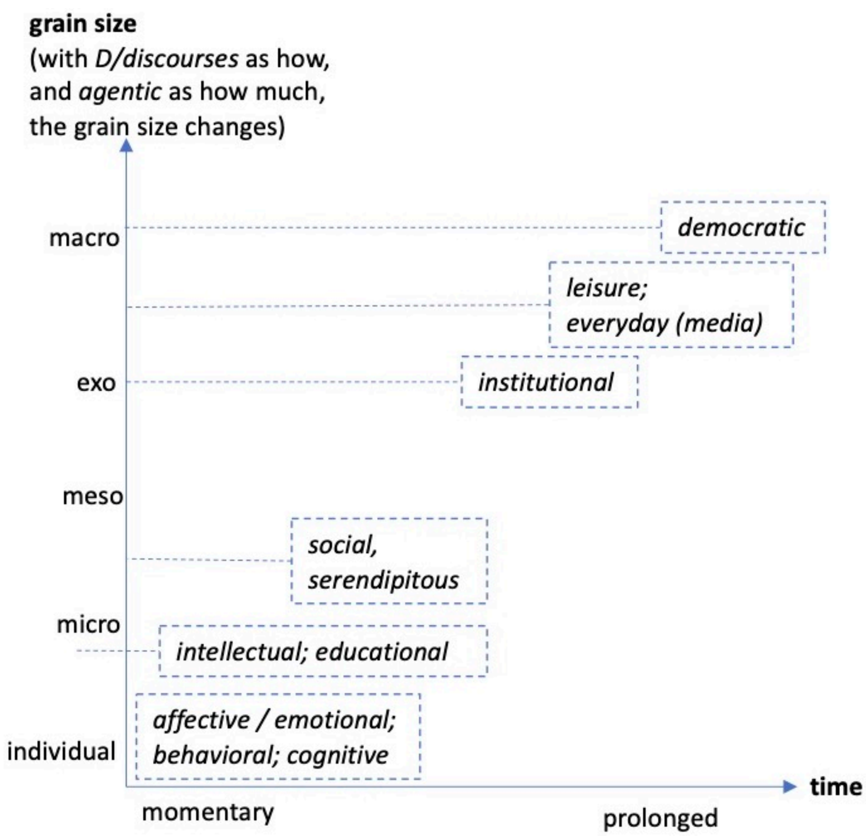
Researchers with primary and secondary schools tend to consider student engagement as a concept related to theories of motivation (Boekaerts, 2016; Eccles, 2016). A three-dimension model of *behavioral, cognitive,* and *affective/emotional* engagement – roughly related to doing, thinking, and feeling – was popular with researchers for over a decade (Christenson et al., 2012). More recently, a dimension of *social* engagement has emerged, related to interactions with classmates and instructors; however, it is unclear as to whether it is a distinct and fourth dimension, or whether it might create a six-dimensional framework (i.e., individual-behavioral, individual-cognitive, individual-affective, social-behavioral, social-cognitive, and social-affective; Fredricks, Wang, et al., 2016).

There is a substantial body of work on student engagement across many academic disciplines (Christenson et al., 2012; Conner & Pope, 2013; Fredricks, Filsecker, et al., 2016), including the natural sciences (Lewenstein & Philips, 2019; Sinatra et al., 2015; Uekawa et al., 2007). Scholars have defined and studied engagement on a variety of timescales, ranging from *momentary* (Schmidt et al., 2018, 2020) to *prolonged* (Humphrey, T., & Gutwill, 2017; Tisdal, 2004). Further, grain sizes of analysis have included individual, small-group, full-class, school, local community, and broader cultures (or, roughly, at the individual-, micro-, meso-, exo-, and macro-levels; see Bronfenbrenner, 1993).

Engagement has strong connections with interest (Järvelä & Renninger, 2014). What makes interest distinct is going beyond psychological variables to include more motivational variables; that is, interest is a progression of stages that manifests both during *and* before activities (Renninger & Bachrach, 2015). An overview of frameworks for engagement, which will be elaborated in section 3.2 and Table 2.1, is presented in Figure 2.2.

Figure 2.2

Frameworks for Engagement across Time and Space(s)



Scholars have not yet come to consensus on an over-arching theory of student engagement itself, instead tending to connect it with theories of expectancy-value, flow, self-determination, and self-efficacy (Eccles, 2016; Nakamura & Csikszentmihalyi, 2014; Schunk & Mullen, 2012; Wigfield et al., 2015). In this study we will primarily consider affective and social engagement as defined by Fredricks and colleagues (Fredricks, Wang, et al., 2016), given the strong social-emotional connections with medium- and long-term outcomes related to coursework and careers (Fredricks et al., 2019; Maltese & Tai, 2010, 2011; Olitsky & Milne, 2012) as well as self-efficacy (Schunk & Mullen, 2012). The current paper aims to contribute to a unified theory by elucidating the relationship between affective, social, and socio-affective engagement (Fredricks et al., 2019), particularly for the domains of science, user-centered engineering, and inventing.

2.3 | Self-efficacy Theory

Despite the individualized nature of the word "self", self-efficacy theory posits a "triadic reciprocal causation" between "individual personal factors", behaviors (including social interactions), and environment (Bandura, 2001, p. 14). Further, self-efficacy theory has been extended to notions of *collective* efficacy for groups, such as communities of teachers (Schunk & DiBenedetto, 2016). The "efficacy" part refers to a person's or group's "beliefs in their capabilities to produce given attainments" (Bandura, 2006, p. 307), such as those described in section 2.1 (i.e., course grades, completed tasks, temperature stability of an insulating device, etc.). Self-efficacy has been strongly connected with medium- and long-term outcomes related to class participation, course achievement, academic and career attainment, and overall well-being (Bandura, 1986;

Britner & Pajares, 2006; Ketelhut, 2007; Pajares & Britner, 2001; Schunk & DiBenedetto, 2016). Though self-efficacy theory has been studied for more than four decades across academic and other contexts, there is still need for research that has finer grain sizes of measurement, includes more culturally and linguistically diverse participants, and meaningfully considers recent advancements in educational technology (DiBenedetto & Schunk, 2018; Schunk & DiBenedetto, 2016, 2020).

Bandura (1993) describes 13 subprocesses for cognitive development through self-efficacy, across four categories: affective, cognitive, motivational, and selection. The most relevant subprocesses for this study are affective processes for anxiety(-management); cognitive processes for comparison (especially with peers); cognitive processes for ability; and selection processes for career, formal, and informal opportunities. In other words, we aimed to foster students' beliefs in their capacity for managing anxiety; their ability to utilize peer feedback and observation; their capabilities in academic knowledge, skills, and practices; and their predisposition towards subsequent chances to engage in practices of science, user-centered engineering, and inventing, across career, formal (e.g., school), and informal contexts (e.g., camps and clubs).

2.4 | Synergies in the Conceptual Framework

As shown in Figure 2.1, we conjecture that educational design would support student engagement in practices of science and user-centered engineering, ultimately leading to the development of self-efficacy in inventing. In addition to broadening these constructs into the emerging field of K-12 invention education (Invention Education Research Group, 2019), we aimed to deepen understandings of student engagement in general. This aim is in response to the “important question” raised by Fredricks and colleagues (2016), as to “whether social engagement is indeed a distinct dimension of engagement, and whether social engagement can be conceptualized as social behavior, social emotion, and social cognition” (p. 12). We hope that these understandings prove useful for design of learning environments, including and beyond the one described in this manuscript.

3 | Review of Empirical Work

3.1 | Empirical work across all disciplines

From its foundations in school-dropout prevention, scholarship on student engagement has flourished in increasingly holistic ways amongst many research approaches, involving learners of all grade levels (Christenson et al., 2012; Eccles, 2016; Pino-James et al., 2019). Although student engagement is often situated in specific disciplines (Christenson et al., 2012; Fredricks, Filsecker, et al., 2016), we acknowledge work done in cross-disciplinary ways, sometimes framed as *academic engagement* or *school engagement.* For example, Conner and Pope (2013) used a “typology of engagement” to study the seven combinations of affective, behavioral, and/or cognitive engagement for 1,426 students in 15 “high-performing middle and high schools” (p. 1430). Using cluster analysis of a survey that included 11 items on student engagement, they found three combinations to be particularly common: *busily engaged* (high-behavioral; 48%), *reluctantly engaged* (moderate-behavioral; 21%), and *fully engaged* (high-affective, -behavioral, and -cognitive; 31%). They emphasized that affective and cognitive engagement did not exist without each other, yet declined to claim any directionality between the two. With strong implications for mental and physical health, the authors noted disparities with respect to gender, race and ethnicity, and school type, which generally favored female, white, grades 6-9, and/or private-school students. Connor and Pope (2013) suggested that reduced class sizes and more positive teacher-student relationships could mitigate such disparities, but that more work was needed before strong assertions could be made. The importance of teacher-student relationships at the individual level is echoed in studies at both the classroom and the school level (Lam et al., 2012; Pianta et al., 2012; Pino-James et al., 2019).

3.2 | Empirical work in science, user-centered engineering, and inventing

Over time, scholars have studied engagement as situated in specific disciplines, including science, engineering, and inventing (J. Bell, Besley, et al., 2019; Christenson et al., 2012; Invention Education Research Group, 2019; Sinatra et al., 2015). Though science, technology, engineering, and math (STEM) are often grouped together, researchers have noted differences in both student- and discipline-based approaches to engagement (Fredricks, Wang, et al., 2016; Roth et al., 2011; Wieselmann et al., 2020). For example, Wieselmann and colleagues (2020) found that disparities with gendered roles were more pronounced in engineering than in science, for a group of two boys and two girls in a fifth-grade unit on electromagnetic cranes. The authors recommend greater structure for role-based learning, and also increased scaffolding for divergent thinking, both of which could counteract gendered stereotypes and foster more equitable participation.

Fredricks and colleagues (Fredricks, Wang, et al., 2016; Wang et al., 2016) developed a four-part survey to measure students' engagement in math and science classes, with respect to emotional, behavioral, cognitive, and social dimensions. Overall, the researchers noted similarities and differences across the two subjects, including comparable levels of cognitive engagement, yet disparities for social engagement, which was greater in science. They observed insufficient differences to merit completely separate scales, meaning the only distinctions would be substituting the word "math" for "science", or vice versa. With evidence that their items were "perceived and interpreted similarly" (Wang et al., 2016, p. 24) for students of various races, genders, socioeconomic statuses, and grade levels, the researchers further showed some predictive capabilities of their measure, including outcomes like achievement, course grades, and intended college major. In particular, behavioral engagement in science was strongly associated with course grades, and emotional engagement in science was connected with career intentions. Still, an overall engagement level was more predictive than any one dimension of engagement.

In a related study, also involving both math and science, Fredricks and colleagues (2018) used a mixed, sequential explanatory design to focus on possible gender differences related to engagement, motivation, and social supports. They conducted an investigation with 38 interviews and 3,833 survey respondents for grades 6-12 students in schools of diverse size, type (district, charter, and private), racial and ethnic composition, and student socio-economic statuses. The researchers found that students were more likely to be engaged if they felt competent for a given task and if they had less fear of "getting [something] wrong or looking dumb" (p. 281). Several influences were stronger for female than for male students, including supportive relationships with teachers and peers, personal relevance of activities, and absence of overly-challenging tasks. The researchers provide evidence that learning environments in science should be student-centered, with appropriately-challenging activities facilitated by engaged teachers.

Moving now to studies that exclusively focus on student engagement in science, there exists a wide variety of nomenclatures and methodologies, as summarized in Table 2.1. Even amongst the studies that align with the four-dimensional framework of affective/emotional, behavioral, cognitive, and social engagement, there are differences in timescales (Humphrey, T., & Gutwill, 2017; Schmidt et al., 2018, 2020; Tisdal, 2004) and in the relative importance of the agency of students, teachers, or educational designers in consideration of broader social and cultural dynamics (Kang et al., 2016; Wade-Jaimes & Schwartz, 2019). While many nomenclatures focus on more individual-, micro-, or meso-level grain sizes, a few frameworks forward more exo-level (e.g., *institutional*) or macro-level (e.g., *democratic*) conceptions of engagement (Lewenstein & Philips, 2019). Still other frameworks emphasize interactions *between* various levels, as moderated by media (Archer et al., 2015), clubs, gardens, or museums (Jack et al., 2014), or cultural and local D/discourses (Wade-Jaimes & Schwartz, 2019). Finally, some scholars study *dis*engagement, thereby defining engagement as the *opposite* of behaviors like "player transformation" (e.g., being a peer-helper at the expense of one's own work), "gaming the system", "off-task behavior", or lack of effort (Gobert et al., 2015, p. 48).

Table 2.1

Selected Nomenclatures for Student Engagement in Science

Publication	Nomenclature	Methodology
(Archer et al., 2015)	*everyday science (media) engagement:* books/magazines, online, TV, etc.	survey → descriptive statistics, regressions, and ANOVAs
(Fredricks et al., 2018; Fredricks, Wang, et al., 2016)	*dimensions:* emotional, behavioral, cognitive, social	induction, deduction, and verification of interviews, then expert validation, then cognitive interviews (2016); mixed, exploratory sequential (2018)
(Gobert et al., 2015)	dis*engagement*: player transformation; gaming the system; off-task behavior; lack of effort	machine learning → pauses, durations, frequencies, resets, and "overall statistics" of an online simulation (p. 50)
(Humphrey, T., & Gutwill, 2017; Tisdal, 2004)	*active prolonged engagement*: emotional, physical, intellectual, social	mixed, naturalistic inquiry, with constant comparative analysis
(Jack et al., 2014)	*leisure engagement in science*: clubs, gardens, museums, etc.	survey → correlations
(Kang et al., 2016)	*intellectual engagement in science*: as designed, launched, and/or enacted	qualitative multiple-case study
(Lewenstein & Philips, 2019)	*contexts*: educational, democratic, institutional	mix of scales and qualitative analyses
(Polman & Hope, 2014)	engagement as *actions, interests, and identifications*	interpretive case studies
(Schmidt et al., 2018, 2020)	*momentary engagement profiles*: sums of affective, behavioral, and cognitive engagement	Experience Sampling Method, followed by cluster analyses (2018) or random-effects modeling (2020)
(Vedder-Weiss, 2017)	*serendipitous science engagement*: includes sense-making, caring, daring, admiring, and (treasure-)hunting	self-ethnography
(Wade-Jaimes & Schwartz, 2019)	engagement in science *D/discourses, practices, and activities*	critical ethnography

With respect to inventing and affective domains, K-12 studies – and especially grades 6-8 studies – to date tend to focus on attitudes and behavioral engagement (Invention Education Research Group, 2019; Kwon et al., 2016). That is, research has emphasized *propensity* to engage (attitudes) or *visible* manifestations of engagement (behavior). One exception is community(-level) engagement (e.g., Nazar et al., 2019), which takes an exo-level approach with systems such as "family social networks" and "neighborhood-community contexts" (Bronfenbrenner, 1993, p. 40). Thus, for invention education, the micro-level system of a school (Bronfenbrenner, 1993) is a scale in need of further exploration, as well as the affective, cognitive, and social dimensions of engagement.

In sum, while there has been substantial scholarly convergence on the more individual or psychological aspects of student engagement in science, user-centered engineering, and inventing (i.e., affective/emotional, behavioral, and cognitive engagement), the possible distinction between affective and emotional engagement is at times unclear. For instance, are the two terms synonymous, or does "affective" overlap more with elements of motivation, perhaps blurring some lines with interest? Further, there remains divergence on the more social dimension(s) of student engagement, both for connections with individual/psychological dimensions and for the salience of various grain sizes. This study seeks to clarify the divergences in affective and social engagement, using dialectical pluralism and mixed research to place conceptual divergences in conversation with each other.

4 | Methods

4.1 | Methodology

Our study of youths' affective and social engagement with practices of science, user-centered engineering, and inventing was informed by a mixed methods metaparadigm of *dialectical pluralism*, in which various paradigms/worldviews of all stakeholders are recognized and embraced (R. B. Johnson, 2017). To enact the metaparadigm of dialectical pluralism, the research team employed design-based research, which has shown potential for bridging theory and practice, and can be considered both a methodology and various sets of methods (Anderson & Shattuck, 2012; Barab, 2014; The Design-Based Research Collective, 2003). Specifically, we took a *cultural psychology* approach (P. Bell, 2004). In this model, interpsychological and intrapsychological processes interact in a specific culture or microculture, such as a classroom or club. That is, there is a dialectic between social and individual processes, within the norms, values, and customs of a given cohort of youth and/or adult(s). This is not to say that a classroom or club is the highest level of consideration; indeed, we acknowledge an *ecological system of development* with individual, intra-group, inter-group, local, national, cultural, and temporal considerations (Bronfenbrenner, 1993).

4.2 | Setting, Participants, and Curriculum

4.2.1 | Mills City[1]

An urban-ring city in the Northeast US, Mills City is culturally and linguistically diverse, with many speakers of English, Haitian Creole, and Spanish, arising from major

[1] All school, city, district, program, teacher, and student names are pseudonyms, unless otherwise noted.

waves of immigration during the mid-1800's (namely from Europe) and in the present day (namely from Central America and the Caribbean). Alongside current immigration is gentrification, especially in former mills being renovated into luxury apartments. In these ways, Mills City is a microcosm of much of past and present US culture. State-provided demographic data about the two middle schools is shown in Table 2.2.

Table 2.2

State-provided Demographics for Mills City

	Race/Ethnicity							Additional demographics				
	Af. Am.	As.	H	M-R, N-H	NA	NH / PI	W	FL NE	ELL	SWD	HN	ED
Central M.S.	10	5	60	<2.5	<2.5	<2.5	30	60	20	20	70	45
Northwest M.S.	10	5	25	5	<2.5	<2.5	55	40	10	15	50	35

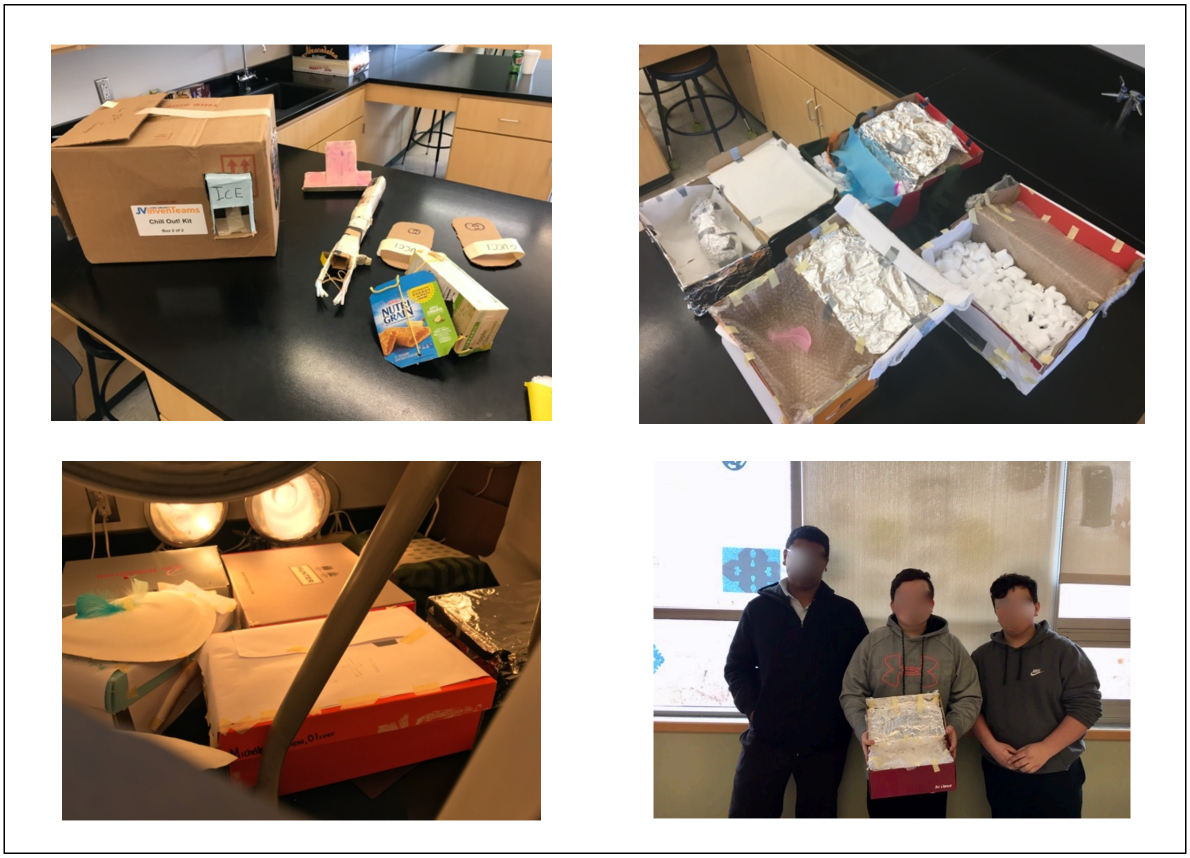
Notes. All numbers are percentages rounded to the nearest 5%, in order to preserve anonymity. Abbreviations are as follows: *M.S.* = Middle School; *Af. Am.* = African American; *As.* = Asian; *H* = Hispanic; *M-R, N-H* = Multi-Race, Non-Hispanic; *NA* = Native American; *NH / PI* = Native Hawaiian / Pacific Islander; *W* = white; *FLNE* = First Language Not English; *ELL* = English Language Learner; *SWD* = Students With Disabilities; *HN* = High Needs; *ED* = Economically Disadvantaged.

4.2.2 Insulating-Device Project

A yearly part of the Grade 7 science curriculum, the insulating device project (IDP) was in its second iteration for the fall 2018 semester. Before each of the first two iterations, an interdisciplinary team of curriculum developers, practitioners, and researchers met for several days in the summer, to adapt the curriculum for Mills City Public Schools students and teachers. The freely-available *Chill Out* curriculum from the Lemelson-MIT JV InvenTeams Program (*not* pseudonyms) centers around inventing an insulating device (Massachusetts Institute of Technology [MIT], 2016). Representative photos are shown in Figure 2.3.

Figure 2.3

Photos from the Insulating Device Project (IDP). Clockwise, from top-left: (a) rapid prototyping; (b) completed devices; (c) team with completed device; (d) set-up for testing.



As in all JV InvenTeams curricula, the *Types of Team Members* framework specifies roles of *Doodler* (of sketches/drawings/diagrams), *Organizer* (of people/objects/tasks), *Talker* (especially to large and/or public groups), and *Tinkerer* (for using tools and materials). Students self-identify their preferred role(s), and instructors are expected to form diverse teams in terms of preferred roles.

Mindful of participating students, the interdisciplinary team adapted the curriculum for racially/ethnically, culturally, and linguistically diverse learners. Table 2.3 has aggregated demographics from the participating four classes; for finer-grained races/ethnicities, see Table S1 in Appendix 4. The enacted curriculum is summarized in Table 2.4. Of the researchers, several specialized in science education, while several specialized in language learning.

Table 2.3

Aggregated Demographics to the Insulating-Device Project (IDP)

	Gender*		
Race/Ethnicity	Female	Male	Total
Latinx	14	10	24
Black	6	8	14
White	23	19	42
Middle Eastern/North African	2	3	5
South Asian & Central Asian	4	4	8
No Response	2	1	3
Grand Total	41	39	80

**Notes.* While there was a non-binary gender category, no students chose it. Six students did not complete any of the pre-survey. For disaggregated self-identifications, see Table S1 in Appendix 4. Table is used with permission from Jackson and Semerjian (2020).

4.3 | Research Design

This study uses a mixed-methods convergent design (Creswell & Plano Clark, 2018), as shown in Figure 2.4. “Convergent” does not mean towards any one “truth”; per dialectical pluralism, we expected a variety of findings based on lived experiences of individuals operating with diverse worldviews (R. B. Johnson, 2017).

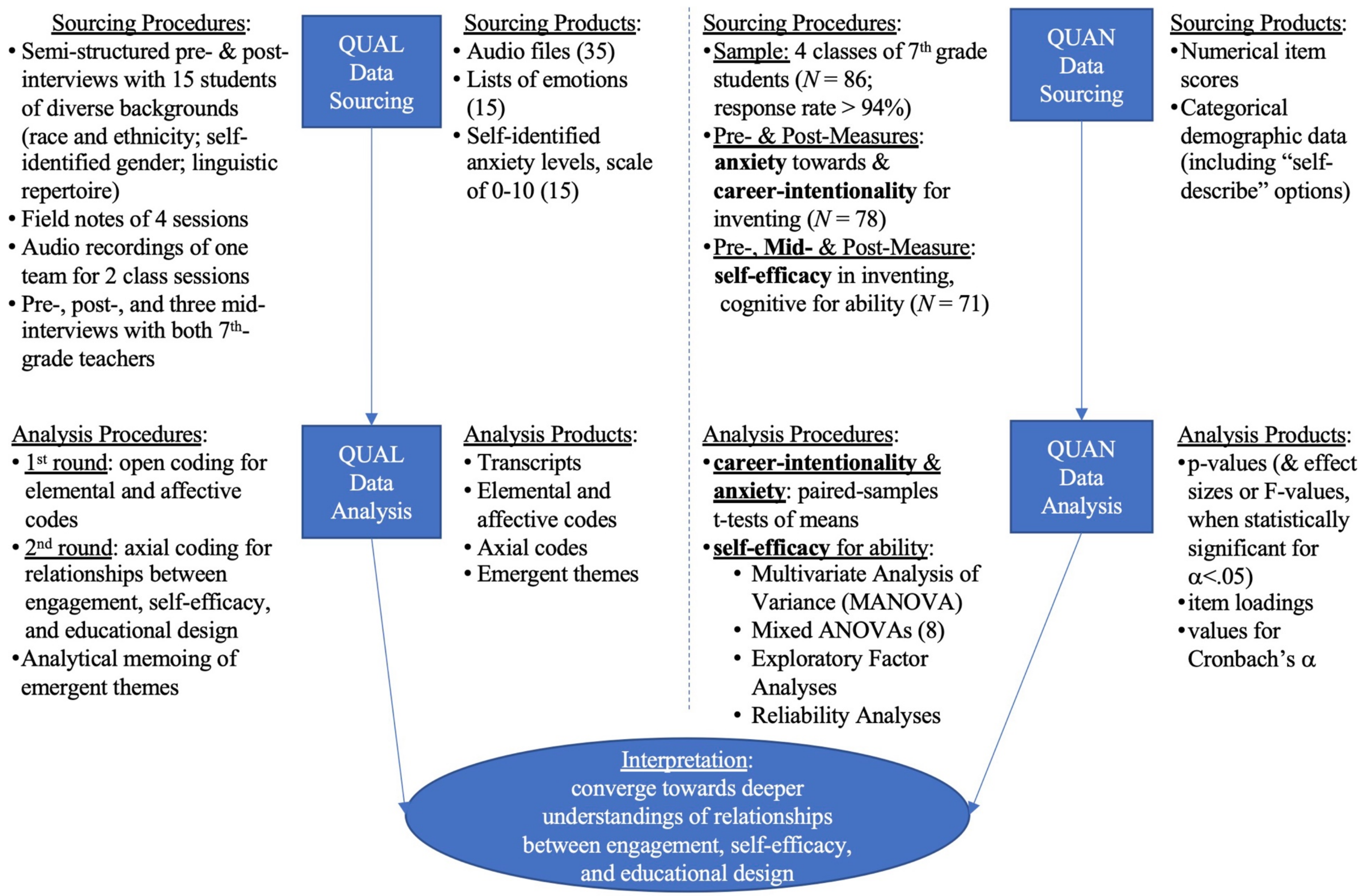
Table 2.4

Curriculum Design for "Insulating Device Project" (IDP)

<table>
<tr><th></th><th>Topics</th><th>Activities</th><th>Domains</th><th>Indiv./Coop.</th></tr>
<tr><td>1</td><td>unit preview</td><td>project overview</td><td rowspan="3">inventing & user-centered engineering</td><td>individual</td></tr>
<tr><td>2</td><td rowspan="2">introduction to inventing</td><td rowspan="2">identify as Types of Team Members; rapid prototypes</td><td rowspan="2">cooperative</td></tr>
<tr><td>3</td></tr>
<tr><td>4</td><td rowspan="6">heat & temperature (thermal energy & temperature; conduction, convection, & radiation)</td><td rowspan="6">*observe diffusion of hot and cold ink in lukewarm water
*measure temperature changes of near-freezing water in various containers
*discuss miscellaneous readings and videos</td><td rowspan="11">physical science</td><td rowspan="8">individual</td></tr>
<tr><td>5</td></tr>
<tr><td>6</td></tr>
<tr><td>7</td></tr>
<tr><td>8</td></tr>
<tr><td>9</td></tr>
<tr><td>10</td><td>insulators</td><td>make "gloves" using vegetable shortening</td></tr>
<tr><td>11</td><td>conductors</td><td>paper and foil on tabletop</td></tr>
<tr><td>12</td><td rowspan="2">budgeting and planning</td><td rowspan="2">choose materials based on tradeoffs of cost and expected performance</td><td rowspan="6">cooperative</td></tr>
<tr><td>13</td></tr>
<tr><td>14</td><td>thermo-electrics</td><td>test Peltier tiles (electrical to thermal energy)</td></tr>
<tr><td>15</td><td>start products</td><td rowspan="2">build, pre-test, and refine final project</td><td rowspan="3">inventing & user-centered engineering</td></tr>
<tr><td>16</td><td>complete products</td></tr>
<tr><td>17</td><td>class contest</td><td>45 min. under heat lamps</td></tr>
<tr><td>18</td><td>start reports</td><td>mock-patent pre-writing</td><td rowspan="2">argumentative writing</td><td rowspan="2">individual</td></tr>
<tr><td>19</td><td>end reports</td><td>mock-patent finalizing</td></tr>
</table>

Figure 2.4

Research Design: Mixed-methods Convergent Design (Creswell & Plano Clark, 2018)



4.3.1 | Data Sourcing

The intervention had pre- and post-interviews, teacher "check-ins" (i.e., brief mid-interviews), observations with field notes and/or audio recordings, and pre-, mid-, and post-surveys. (Protocols are in the Appendices 1 through 3.) Interview protocols were designed by the research team within the interdisciplinary field of invention education, which incorporates elements of user-centered engineering to create novel technologies that benefit persons, groups, communities, or societies, often in ways that are economically scalable (Committee for the Study of Invention, 2004; Invention Education Research Group, 2019). Within the broader field of invention education, we focused on youths' conceptions of inventing, attitudes toward inventing, and engagement in inventing, as well as adults' concepts of invention education. In addition to convenience sampling per returned permission forms, interviewees were chosen for variation (Creswell, 2013) with respect to race/ethnicity, gender, and parent/guardian education levels. Two students declined post-interviews (denoted as "pre-only"). Three students who were part of a focal team were not pre-interviewed, and therefore completed only a post-interview ("post-only"). Available demographic information of the 15 interviewees is shown in Table 2.5.

Relating to this study's conceptual framework, *conceptions* included elements of youths' practices; *attitudes* included self-efficacy towards inventing; and *engagement* was operationalized as affective, behavioral, cognitive, or social. Suggested vocabulary for affective engagement came from "The Feeling Wheel" by Willcox (n.d.). The wheel consists of an inner ring of six primary emotions (*sad*, *mad*, *scared*, *joyful*, *peaceful*, and

Table 2.5

Demographics for Interview Participants

Pseudonym	Race / ethnicity	Gender	Parent/Guardian Educational Attainment
Nuru (pre-only)	Middle Eastern / N. African	female	high school, college
Shaila (pre-only)	South Asian	female	college
Andre	Black, Caribbean	male	high school, college
Daniela	Hispanic/Latino	female	high school, college
Jeff	white	male	high school, college
Jay	white	male	high school, college
Morgan	white	female	college
Matty	white	male	college
Alexander	white	male	“I don’t know”
Paz	Hispanic/Latino	female	“I don’t know”
Araceli	Black, African, African-American	female	“I don’t know”
Timmy	Hispanic/Latino	male	“I don’t know”
Gary, Jimmy, & Ludo	<unreported>	male	<unknown>

powerful), a middle ring of 36 secondary emotions, and an outer ring of 36 tertiary emotions, for a total of 78 emotions. Interviewees were also given the option to self-describe an emotion if it was not listed. (For the full Feeling Wheel, see Appendix 1, or refer to the link in the References section.) In general, pre-interviews were conducted before pre-surveys, to avoid having the more exogenous nature of the survey items corrupt the more endogenous spirit of the interview items.

We customized pre- and post-interview items for the two participating teachers at Northwest Middle School. One of the teachers, Ms. Kumar, was new to full-year teaching (having some previous long-term substituting experience), the school itself, and the curriculum. Thus, her items lacked some of the more targeted items shared with Mr. Braun, who was in his third year in the building and second year with the IDP curriculum.

The surveys focused on youths' conceptions of inventing, attitudes toward inventing, and engagement in inventing, using subscales that had performed well the previous year (Jackson & Semerjian, 2020). Within attitudes, we adopted a self-efficacy subscale per self-assessments from the curriculum (Cronbach's α=.90); we operationalized anxiety toward inventing through the modified Attitudes Towards Science Inventory (mATSI; Weinburgh & Steele, 2000), substituting the word "inventing" for the word "science" (Cronbach's α =.82); and we measured intentionality toward inventing with a subscale based on the *reasoned action approach* of Fishbein and Ajzen (2010) (Cronbach's α =.85). The absence of engagement- or practices-related items is mitigated by the prominence of engagement and practices in interviews and observations. Self-efficacy items were present in the pre-survey, post-survey, and mid-survey. The mid-survey was administered towards the end of the more science-based portion of the project (i.e., Day 10 of 19), shortly before the beginning of the more design-based portion.

Observations focused on youths' practices and engagement. Though self-efficacy was not explicitly targeted during observations, evidence of its development was possible through audio recordings, in addition to participant-observers' field notes. Affective, behavioral, and cognitive engagement together had one column in each observation protocol. On the other hand, social engagement was centered on the participation roles dictated by the curriculum, namely *Doodler* (drawing and sketching), *Organizer* (of materials, persons, and tasks), *Talker* (especially between groups and with the general public), and *Tinkerer* (putting things together and/or taking them apart) (Massachusetts Institute of Technology [MIT], 2016).

Practices were not an explicit focus of the observation protocol, but practices tend to overlap with behavioral, cognitive, and social engagement. For example, the NGSS practices of *plan and carry out investigations*, *analyze and interpret data*, and *obtain, evaluate, and communicate information* (NGSS Lead States, 2013) align well with behavioral, cognitive, and social engagement, respectively (allowing for some co-incidence in dimensions of engagement; e.g., investigations can be conducted in socially-engaging ways). During the IDP, students imagined human needs for food and medicine, especially in contexts of natural disasters, power outages, or electricity access around the world. For full observation protocols, see Appendix 3. Finally, alignment between the conceptual framework and the data sourcing is shown in Table 2.6.

4.3.2 | Data Analysis

The overall case is the Insulating Device Project (IDP), bounded in time and participants as described in Section 4.2 above ("Setting, Participants, and Curriculum").

Table 2.6

Alignment of Data Sourcing with Conceptual Framework

	Interviews			Surveys			Observations
	Pre	Mid	Post	Pre	Mid	Post	Mid
affective engagement	+	?	+	x	x	x	+
behavioral engagement	?	?	+	x	x	x	+
cognitive engagement	?	?	+	x	x	x	+
social engagement	+	?	+	x	x	x	+
self-efficacy	?	?	+	+	+	+	?
practices of science, user-centered engineering, & inventing	+	?	+	?	?	?	+

Notes. "+" = a target of the instrument, "?" = possible coverage through open-ended or tangential items, "x" = no opportunity for response. For example, self-efficacy was targeted in all surveys via five-point Likert-style items for "I can…" statements; it might have been evident in relatively open-ended interview items like, "How do you think you might feel about inventing?" (e.g., confident, powerful, etc.); and it could be shown in student utterances during observations, such as "I'm good at this [inventing]."

We started with quantitative analyses, beginning our mixed approach to convergence through an explanatory lens (Creswell & Plano Clark, 2018). For the three subscales described in "Data Sourcing" above, we used IBM® Statistical Package for the Social Sciences version 27 (SPSS®). Firstly, we performed t-tests of means for the two subscales that only appeared on the pre-and post-surveys, namely self-efficacy through selection (of future inventing opportunities) and self-efficacy through anxiety. Secondly, for the subscale that appeared on pre-, post-, and mid-surveys (i.e., self-efficacy through ability), we conducted a multivariate analysis of variance (MANOVA) for all eight items together, followed by eight repeated-measures analyses of variance (ANOVAs) for each individual item. We took this two-step procedure to first look for any overall changes, and then to gain finer-grained insight into micro-dynamics of those changes.

Thirdly, we performed an exploratory factor analysis (EFA) for the subscale on self-efficacy for ability, in order to understand relationships between the three main disciplines of the project (i.e., inventing, science, and user-centered engineering). After the initial EFA revealed two factors onto which items loaded relatively weakly, we ran additional analyses that forced two- and three-factor models, respectively. Details for EFAs are included in Table S2 of Appendix 4.

Our fourth and final quantitative stage involved analyses of reliability, using Cronbach's α. Initial analyses indicated that removing any one item would decrease reliability. Subsequent analyses showed that removing items cumulatively also resulted in lower reliabilities. Details for reliability analyses are included in Table S3 of Appendix 4.

Qualitative analyses began with transcribing all interviews and observations for which research permission was granted by participants. Automated transcription by REV.com was followed by verification from our research team, for a total of 150 minutes of teacher pre-, mid-, and post-interviews, 243 minutes of student pre- and post-interviews, and 67 minutes of small-group work-time. We consider transcription to be part of analysis, as judgement calls were made about what counted as "inaudible", and also how to punctuate utterances.

In our first round of coding, transcripts were deductively coded per our conceptual framework (i.e., design considerations of the Social Infrastructure Framework; processes of developing self-efficacy; and dimensions of student engagement). As the district curriculum is well aligned to the Next Generation Science Standards (NGSS; NGSS Lead States, 2013), we considered engagement in its eight

Science and Engineering Practices, as well as practices of inventing per the unit curriculum (Massachusetts Institute of Technology [MIT], 2016). We also added inductive codes, especially value codes (Saldaña, 2009) as participants spoke of what "inventing" meant to them, and of their goals for the project (aesthetics, beneficence, completeness, cultural competence, etc.). Further inductive codes emerged around collaboration and competition, through process coding (Saldaña, 2009) that aligned well with social interdependence theory of Johnson and Johnson (2009), including codes like "dependence", "independence", "interdependence", and "isolation/helplessness". Analytical memos were written after coding all student interviews and each set of teacher interviews, that is, after three data subsets of roughly equal size.

In our second round of coding, we used pattern coding to note which subcomponents of our conceptual framework arose most prominently, then axial coding to make connections between those subcomponents (Saldaña, 2009). Each axial code included one of affective, behavioral, cognitive, or social engagement, *and* one of the four focal processes for self-efficacy (ability, anxiety, comparison, and selection processes; Bandura, 1993) *or* one of the three most salient design considerations for the Social Infrastructure Framework (*the planned learning activities*, *how learning and knowledge are conceptualized*, and *how a student's social identity is understood*; Bielaczyc, 2006). We then wrote further analytical memos (Saldaña, 2009) to synthesize results from student interviews, teacher interviews, classroom observations, and quantitative analyses. Ultimately we arrived at deeper understandings that we organized in a *variable-oriented* manner (Miles et al., 2014), namely grouped by dimensions of engagement and processes of self-efficacy.

5 | Results

This study reports on a grade seven project for inventing insulating devices, centering on student engagement, with implications for self-efficacy and educational design. During data analysis, we found that students' collaboration practices aligned well with social interdependence theory (D. W. Johnson & Johnson, 2009), wherein teams can pursue goals in ways that are mutually beneficial or harmful (*social interdependence*), individually isolated (*social independence*), mono-directional from some teammate/s to other/s (*social dependence*), or having little to no impact (*social helplessness)*. Thus, we weave a thread of social interdependence theory throughout this section, in particular as it relates to social aspects of affective, behavioral, and cognitive engagement. Findings for engagement are summarized in Table 2.7, and also presented sequentially and in a narrative fashion in subsections 5.1-5.3. Subsection 5.4 includes our shorter-term findings about self-efficacy, with connections as to how that self-efficacy might develop over longer timescales.

5.1 | Affective Engagement: "You can be energetic, but also relaxed, too." –Jay

Even before the project began, students felt excitement and anticipation as they brought shoeboxes to be frames for the insulating devices. However, they soon experienced anxiety when viewing the project packet, which was roughly 45 double-sided sheets of paper. Upon reassurance that the packet would be explored over several

Table 2.7

Relationships of Engagement with Educational Design of Planned Learning Activities

Activities	Affective Engagement	Behavioral Engagement	Cognitive Engagement
Pre-unit anticipation	• excitement about project's hands-on and group-oriented structures	• bringing-in shoeboxes from home	• wondering when unit would start
Packet-distribution	• anxiety about size of packet, work-load, and work-rate	• some writing on paper • some asking for accessible format (i.e., Google Doc)	• struggles with accessibility (especially for paper and PDF versions)
Rapid prototyping	• creativity and spontaneity in a relaxed atmosphere	• sharing ideas and reaching compromises	• brainstorming, evaluating, and synthesizing
Packet-completion	• frustration, if doing *more* than perceived fair share of tasks • boredom, if doing *less* than perceived fair share of tasks • trust and faith, if sharing of tasks is perceived as fair	• completing, if doing *more* than perceived fair share • copying, if doing *less* than perceived fair share • discussing, if sharing of tasks is perceived as fair	• internalizing, if doing *more* than perceived fair share • transcribing, if doing *less* than perceived fair share • sense-making, if sharing of tasks is perceived as fair
Building	• enjoyment with hands-on, cooperative, and novel creating	• choosing materials • assembling the device • returning excess materials • trading-with *or* *donating-to* peer-groups	• designing solutions (to minimize temperature increase, for a given budget)
Contest	• accomplishment for 1st-place in cluster or class • moderate pride or mild disappointment for places 2+	• filling bottle with water • calculating differences in temperatures	• analyzing and interpreting data (pre- and post-trial temperatures for ~24 teams per class)

Patent-writing	• personal sense of responsibility • some feelings of overwhelm	• four versions of assignment, with varying types of scaffolding	• arguing from evidence (for usefulness, uniqueness, and practicality of invention)
Poster	• comfort with linguistic repertoires	• using more colloquial language (as compared to patent-writing)	• communicating (especially about conduction, convection, and radiation)
Post-unit reflection	• varied degrees of confidence in abilities • varied phases of interest and career-intentionality • moderate levels of anxiety	• retrospection on social interdependence, independence, isolation, accountability, and competition	• varied manifestations of *meta*cognition • one teacher's framing as preparation for future interdisciplinary learning

weeks, and with completion of some rapid-prototyping activities, anxiety was lessened as creativity surged. For groups that completed foundational science-focused activities in socially interdependent ways, teammates expressed feeling faith and trust. On the other hand, socially independent or dependent groups felt loneliness, boredom, and frustration. These differences provide evidence that affective engagement has both individual and social aspects (i.e., individual-affective and social-affective, as opposed to affective and social as distinct), addressing a need for further clarity on social factors for student engagement (Fredricks et al., 2019; Fredricks, Wang, et al., 2016).

After completing the more science-focused activities (i.e., *constructing explanations* about conduction, convection, and radiation), teams began more engineering-focused activities (i.e., *designing solutions* for minimizing transfer of thermal energy). During assembly of insulating devices, teammates showed joy and enthusiasm, as evidenced in teacher interviews, student interviews, and data generated from video (e.g., smiling, laughing, yelling, joking). For the groups whose devices performed well in class- and cluster-wide contests, the positive emotions continued with feelings of accomplishment and pride, in degrees that mirrored their placings (e.g., first-place groups expressed the strongest positive feelings). Conversely, groups with poorer-performing devices experienced disappointment.

The final phase of the project – the more literacy-focused activities – included a wide range of emotions, often linked with students' linguistic repertoires. Given the monolingual, US-English dominant language practices of the class, some emergent multilingual learners felt overwhelmed by the requirements of the patent-writing activity. In response, Mr. Braun and Ms. Kumar scaffolded four versions of the activity, supporting students who were classified as having limited English proficiency. Further, teachers concluded with a promotional-poster based activity, which empowered students to communicate through more visual means and less formal grammatical structures. Unsurprisingly, students showed less anxiety when using this medium to express their understanding, through which they used expanded linguistic repertoires.

Ultimately, the project engendered a mix of emotions. Students felt energetic yet relaxed, as noted by Jay in this subsection's header; they felt excitement with building that at times was mixed with disappointment from evaluating; and they felt anxious about the more procedural work, yet comforted if their classmates and teammates supported each other. The comfort is exemplified in Daniela's statement, "there was other people working with me that could help me, and it wasn't really something to get anxious about". The excitement mixed with disappointment was illustrated by Gary, Jimmy, and Ludo, who felt “successful” when they won their class contest, then described their non-winning cluster-wide performance as “not too bad”. Though these emotions might be common to project-based learning, we argue that the added creativity, practicality, and relevance of invention education fosters engagement to a greater degree than do more structured projects. Further, the interplay of individual emotions and team moods supports the warrant for individual-affective and social-affective dimensions of student engagement.

5.2 | Behavioral Engagement: “[Inventing] is not my thing… But I do like the experience of [working on the insulating device].” –Paz

Having established a foundation of pre-unit dispositions and instantaneous feelings (i.e., affective engagement), we now proceed to results for behavioral engagement. Before the project began, this type of engagement consisted of students bringing-in shoeboxes, an encouraged yet not required behavior. As the unit commenced, some students quickly started writing in the paper-based packet, while others requested an electronic version (often for accessibility reasons). During the launcher activity of rapid prototyping, students showed behavioral engagement by sharing ideas (both orally and written) and reaching compromises.

When it came time to work on the packet in groups, the more socially interdependent groups completed the prompts by discussing answers before writing them down. Contrastingly, more socially independent groups wrote their answers without talking, and socially dependent groups had at least one teammate directly copying answers from others. Thus, some behaviors that could be individualized in identical ways (e.g., the act of writing on a worksheet) could represent very different levels of social-behavioral engagement (e.g., copying vs. collaborating).

When students began building their insulating devices (i.e., the more engineering-intensive phase of the project), behavioral engagement looked and sounded like students choosing materials, attaching the materials to their shoebox, returning or exchanging excess materials, and bargaining-with or donating-to fellow groups. It is unclear why classmates would freely give materials to other teams with whom they were competing; perhaps social connections such as friendships overruled academic incentives such as contests. During the contests themselves, students were tasked with filling water bottles with near-freezing water, then calculating temperature differences after approximately 30 minutes under heat lamps. In each of these cases, the same behaviors could be qualitatively different if they showed a more individual-behavioral nature (e.g., making trades unilaterally) or a more social-behavioral orientation (e.g., discussing with teammates the terms of a potential trade).

Behavioral engagement became most distinct to inventing when students completed the poster and patent-application. The aforementioned four scaffolds for the patent-application meant that some students wrote paragraphs on their own, while others used aids such as graphic organizers or sentence stems/frames. These aids included language specialized to technological inventing (“intellectual property”, “reduced to practice”, etc.). Also, the aforementioned poster had as its target audience potential users/beneficiaries of the invention, rather than the class’s teacher or some hypothetical “engineering/scientific community” or “professional engineers/scientists”. The more authentic audience both permitted and compelled students to use colloquial grammatical constructions that nonetheless communicated canonical concepts of science, user-centered engineering, and inventing. In the words of Ms. Kumar, "after all that heavy writing for one week [for the patent-application], I gave [students] the posters. So, it kind of eased [the pressure] on them, and they used all the words [they wanted to use]."

In post-interviews, students and teachers alike were well aware of which teams and teammates engaged through social interdependence, independence, or dependence. Some of those differences are evident in this subsection's lead quotation from Paz, who enjoyed the more interdependent nature of the project, despite her not identifying as an independent inventor. In fact, Paz's pre-interview anticipated one of the benefits of interdependent inventing, namely that "working in groups…is better than working alone, because you can get ideas from each other… talk about [a project], work together as a team". Exchanging ideas is one key way in which a social-behavioral dimension of engagement would differ from an individual-behavioral dimension, and which might foster increased cognitive engagement, the subject of our next subsection.

5.3 | Cognitive Engagement: "…maybe I should provide multiple gateways of doing this [summative assessment]." –Ms. Kumar

Cognitive engagement includes *meta*cognitive reflection upon other forms of engagement, so we present its findings last for forms of engagement. Even before the unit began, students showed cognitive engagement by wondering when the unit would start, as shoeboxes piled-up and Mr. Braun's classes began the project before Ms. Kumar's classes. When the unit started, the aforementioned requests for an electronic version of the packet indicated both cognitive struggles with accessing the provided format *and* metacognitive awareness of more accessible formats. During the rapid-prototyping activities, students engaged in cognitive tasks such as brainstorming ideas, and then evaluating and synthesizing those ideas. When completing the packets, interview and observational data suggest that more socially interdependent groups engaged in expansive sense-making (Bang et al., 2017), compared to more straightforward internalization by socially independent groups (Vygotsky, 1978), or mere transcribing(/copying) by socially dependent teammates. In sum, social-cognitive engagement could be viewed as more than the sum of its individual-cognitive parts.

The more engineering- and literacy-intensive parts of the project demonstrated how invention education can closely align with the NGSS. When planning and building the insulating devices, the students would *design solutions*; based on contest results, they would *analyze and interpret data*; the patent-application included *argument from evidence*; and the poster promoted expansive notions of how to *communicate information* (NGSS Lead States, 2013). In this example, we see how invention education aligns with culturally sustaining pedagogy (Paris, 2012); students could *maintain* their cultural practices in identifying meaningful users/beneficiaries and using colloquial language in the posters, while also *extending* their proficiencies in dominant norms. We argue that such alignment is inherent to invention education, and that the inclusion of more social and empathic elements, which the NRC *Framework* delegates to “the level of curriculum design” (National Research Council, 2012, p. 248), can be promoted through an invention education approach to teaching and learning.

One potential longer-term benefit of the project was identified by an 8th grade science teacher, who told Ms. Kumar that the unit might prime 7th graders to think in interdisciplinary ways. That is, by engaging in a project wherein invention combined science, user-centered engineering, and literacy, students would have a reference point for interdisciplinary projects in 8th grade and beyond. Another possible longer-term benefit was described by Ms. Kumar in this subsection's opening quotation. Both students and teachers alike recognized the value of multiple modes of summative assessment (patent-writing, posters, and some sub-unit mini-quizzes not yet mentioned), in metacognitive ways that support the representation of cognitive concepts (Rodriguez, 2015) and development through self-efficacy's expression via cognition about ability (Bandura, 1993), the latter of which is detailed in the following subsection.

5.4 | Self-efficacy: "We were struggling a lot, at the beginning. And we didn't really, like, get it, kind of. But then we pulled through." –Jimmy

To look at deeper and longer-term effects of engagement, we used surveys, interviews, and observations to examine students' cognitive development through self-efficacy via cognitive processes for ability, affective processes for anxiety(-management), and selection processes for careers (Bandura, 1993). We proceed in that order, as students began the unit with conceptions about their invention knowledge, skills, and practices; they varied in their ways of processing anxiety during the unit, even though overall changes were not statistically significant at the α=.05 level; and their orientation towards invention careers has post-unit implications. Inferential statistics are shown in Table 2.8, converged with qualitative results in the main body of this text.

Descriptive statistics of self-efficacy through ability beliefs are summarized in Figure S1 of the Appendix 5.

5.4.1 | Self-efficacy through ability beliefs

We anticipated that each of the eight self-efficacy items would align with one of three domains: user-centered engineering, science, and inventing. Taking a relativistic and practical approach to effect sizes (Cohen, 1990), we note that our observed effect sizes are comparable to those from interventions of similar duration (Jackson & Semerjian, 2020; Kwon et al., 2016; Tomas et al., 2011) while understandably more modest than effects from year-long and school-wide efforts (e.g., Lamb et al., 2015). Unsurprisingly, the greatest effect size was for ability to "build a portable cooling device". The next two greatest effects were primarily within the domain of science, followed by some lesser effects in the domain of inventing (including one of the two statistically insignificant results). These data suggest that the unit was successful in addressing state-mandated needs for science and engineering, but that more emphasis, time, or both would be necessary to increase students' self-efficacy with respect to inventing.

5.4.2 | Self-efficacy through anxiety management

As noted above, the mean changes in self-reported anxiety (Weinburgh & Steele, 2000) from pre- to post-survey were not statistically significant at the α=.05 level. Qualitative data suggest that the anxiety level might have increased due to students' personal factors, if it had not been offset by environmental factors. As noted by Paz, "I'm obviously not going to be not anxious at all. There's always going to be, like, some worry

Table 2.8

Questionnaire Statistics on Self-efficacy for Ability (Ab), Anxiety (Anx), and Career-Intentionality (CI)

Item #	Questionnaire item: "I can…"	Main Practice	Main Domain	*F*	*df*	*ω*
Ab-1	…make something useful out of material like cardboard, wood, or fabric.	experimenting	inventing	–	–	–
Ab-2	…use tools such as thermometers & utility knives.	investigating	user-centered eng.	–	–	–
Ab-3	…work as part of an invention team.	transgressing	inventing	3.94*	2	.15
Ab-4	…test the thermal insulating and conducting properties of various materials.	researching	science	11.43***	2	.29
Ab-5	…demonstrate heat transfer.	researching	science	13.18***	2	.32
Ab-6	…build a portable cooling device.	experimenting	user-centered eng.	37.49***	2	.49
Ab-7	…identify a real-world need.	empathizing	inventing	7.53***	2	.22
Ab-8	…apply my skills to solve a real-world problem.	transgressing	inventing	3.57*	2	.12
All (*N*=71)	N/A	N/A	N/A	7.54***	16	N/A

Items	Instrument	*g*
Anx-all (*N*=78)	modified Attitudes Towards Science Inventory, anxiety subscale; "inventing" substituted for "science"	–

Items	Instrument	*g*
CI-all (*N*=78)	novel instrument; for details, see Jackson and Semerjian (2020) and Appendix 2.	-.28*

Note. *p<.05, **p<.01, ***p<.001, and "–" denotes p≥.05.

in me. So, like, just because this [invention] came out good doesn't mean the other one will come out good." Students expressed anxiety about completing the project, earning high grades, and competing well in the contest. An increase in anxiety is generally undesirable, for if it is poorly managed, it can inhibit learning and development (Bandura, 1993).

Fortunately, the team-based educational design in part offset anxiety, with one example from Daniela: "…there was other people working with me that could help me, and it wasn't really something to get anxious about, because [inaudible] helped me do everything, and my classmates helped me, too." Further, a full-class Gallery Walk led by Mr. Braun seemed to lessen students' anxiety around giving and receiving constructive criticism. Mr. Braun was present throughout the activity, ensuring that feedback was framed in generative ways. Thus, the lack of a statistically significant change in anxiety could be considered a desirable result, as educational design elements functioned to counteract anxiety inherent to students' general academic concerns and specific nervousness at the novelty and competitiveness of the project.

5.4.3 | Self-efficacy through selection (of careers)

As shown in Table 2.8, career intentionality *decreased*, with -.28 for Hedge's *g*. Upon initial inspection, this result appears undesirable, given the potential for approaches like invention education to broaden participation and interest in STEM-related fields (Blumenfeld & Sotelo, 2017; Invention Education Research Group, 2019; Tytler & Osborne, 2012). However, some caution is merited due to students' naïve conceptions of inventing from the pre-interviews. That is, the intervention may have served to provide more realistic and nuanced ideas of how technological inventing tends to occur in professionalized contexts, especially as related to patenting and economic innovation (Committee for the Study of Invention, 2004; Invention Education Research Group, 2019).

This short-term decrease in career intentionality toward inventing might be a precursor to subsequent increases, as self-efficacy through *performance accomplishments* should increase with additional experience, which in turn could develop *emotional arousal* towards careers (Bandura, 1977). Further, work on interest and career-intentionality with youth from similar demographic backgrounds suggests that it often takes years of sustained programming or other supports to make substantial and persistent increases in those affective domains (Aschbacher et al., 2010; Blustein et al., 2013; Mark et al., 2014). So, while caution is still merited given the substantial decrease in career intentionality for a relatively short intervention, there is reason for optimism that future classes, camps, and clubs based on inventing could reverse the initially negative trend. This possibility is captured by the words of Jimmy from this subsection's header, namely that youth might "[struggle] a lot, at the beginning", then eventually "[pull] through". More work is needed to examine longer-term effects of invention education, especially for historically marginalized groups in STEM (Blumenfeld & Sotelo, 2017; Invention Education Research Group, 2019).

5.5 | Closing Remarks for Results

In sum, the results for engagement provide clear distinctions between individually- and socially-oriented dimensions for each of affective, behavioral, and cognitive engagement. The self-efficacy results provide insight into the interdisciplinary nature of inventing, especially with respect to how disciplines are emphasized in curriculum (in this case, science and user-centered engineering). Even the results without statistical significance provided insight into processes of developing self-efficacy for inventing, when considering qualitative alongside quantitative data, in ways that are needed to provide added depth to self-efficacy theory in education (DiBenedetto & Schunk, 2018; Schunk & DiBenedetto, 2016, 2020; Schunk & Mullen, 2012). In this section we shared some of the clearer and more locally-situated connections with educational design and self-efficacy theory, to which we add more transferrable conjectures in the Discussion section.

6 | Discussion

In this paper we reported on seventh-graders' engagement in a project to invent insulating devices, as connected to their development through processes related to self-efficacy. Our design-based approach helps to mediate theory and practice, with implications towards "trajectories for change" in educational design (Bielaczyc, 2013, p. 258). In this section we first describe design considerations (Bielaczyc, 2006) that are salient for changing instruction from more traditional, monodisciplinary models towards more interdisciplinary and engaging approaches. Second, we share conceptual implications for student engagement, especially as related to individual|social dialectics and to whether or not "social engagement" is a distinct dimension. Finally, we include theoretical implications for self-efficacy theory.

6.1 | Implications for Educational Design

Thinking with the aforementioned Social Infrastructure Framework by Bielaczyc (2006), per procedures described in the Methods section we identified three of the 20 design considerations that were particularly salient: *the planned learning activities*; *how learning and knowledge are conceptualized*; and *how a student's social identity is understood*.

6.1.1 | The planned learning activities

The planned curriculum (Massachusetts Institute of Technology [MIT], 2016), after accommodations and modifications by Mr. Braun, Ms. Kumar, and the research team, resulted in an "activity selection" that was "semi-structured" (Bielaczyc, 2006, p. 314). This moderate degree of structure supported pursuit of both normative and endogenous goals (Enyedy & Stevens, 2014), such as those mandated by the NGSS or co-constructed by participants, respectively. Framing the central problem as one of inventing served as a means of preserving student agency, as the seventh-graders worked to create personally meaningful devices (for medicine transportation, food storage, disaster relief, etc.).

While it is a common design choice (Reiser & Tabak, 2014) that activities "differ according to the needs of different students" (Bielaczyc, 2006, p. 314), the invention framing was particularly suitable for scaffolding in summative assessments. Given the connections between inventing and patent-writing, presenting, and other promotion or publicity (Committee for the Study of Invention, 2004; Invention Education Research Group, 2019), the formats of patent-application, slideshow, and poster were closely aligned with the entrepreneurial spirit of the project. Students had multiple opportunities to express their learning, often in ways that allowed them to leverage broad linguistic repertoires (e.g., slang, slogans, and branding for advertising purposes).

6.1.2 | Conceptions of learning and knowledge

To address the question, "What does it mean to 'know'?" (Bielaczyc, 2006, p. 314), an invention approach has an explicit focus on being useful, novel, and not obvious (Committee for the Study of Invention, 2004; Invention Education Research Group, 2019). In other words, in being challenged to design the somewhat ambiguously termed "insulating device", students were positioned as constructors of new knowledge, rather than replicators of existing knowledge. This positioning broadened the notion of what "counted" as science, user-centered engineering, and inventing, and also embraced learning from failure and mistakes. In other words, the "process of learning" (Bielaczyc, 2006, p. 314) was expanded, along with knowledge generated by that process.

One drawback of the educational design was the awarding of prizes exclusively for effectiveness at a fixed budget (i.e., minimum degrees of temperature increase for a bottle of near-freezing liquid water, with a $30 hypothetical budget). Prizes or other recognition for aesthetics, marketing, or additional arts- and business-related topics could have increased both engagement and development of self-efficacy. Further, a prioritization on efficiency could have encouraged more sustainable designs (e.g., calculating the degrees of temperature increase *times the number of dollars spent*, with lower being better). Thus, a project that already includes a focus on reliability and cultural matters can also include social and environmental impacts and trade-offs from (over)using materials, toward what Gunckel and Tolbert (2018) call “a dimension of care” for engineering (p. 954).

6.1.3 | Understandings of a student’s social identity

When participating in the learning activities amidst invention-based conceptions of learning and knowledge, students viewed themselves and others variously “as learning resources, as team members, [or] as competitors” (Bielaczyc, 2006, p. 314). In other words, youth implicitly positioned themselves, groupmates, and other classmates on continua of agency and helplessness, contribution and slacking/loafing, and cooperation and competition, as previously described in connections with social interdependence theory (D. W. Johnson & Johnson, 2009). Though the enacted curriculum included examples of younger, “everyday” (not-yet-famous), and more collaborative inventors compared to stereotyped narratives (Invention Education Research Group, 2019), data generated from interviews and observations suggested that youth still had relatively individualistic conceptions of inventing. More explicit examples of, and attention to, collective notions of inventing are needed, in order to promote improvement through cooperation – a hybrid of community and competition that Hutter and colleagues (2011) call *communitition.*

6.2 | Implications for the Individual|Social Nature of Student Engagement

In describing the relation between educational design and student engagement, Pino-James and colleagues (2019) summarized that “infusing the principles of meaningfulness, agency, competence, and positive peer- and teacher-student relationships into instruction can be a powerful way to foster adolescent behavioral, emotional, and cognitive engagement with classwork.” (p. 117) The curriculum frame of inventing promotes meaningfulness by focusing on the needs of a user/beneficiary; it promotes agency by emphasizing the novelty needed for a contrivance to “count” as an invention; it fosters competence by requiring students to leverage science and engineering concepts to make the invention useful; and it promotes prosocial relationships when structured in a way for teammates to compete best when they cooperate with each other (and potentially their other classmates as well). Further, the curriculum forwards counter-narratives to the stereotype of inventors being older white men working alone or with invisiblized teammates, especially when instructors include examples of younger and more racially/ethnically and gender-diverse inventors (as did Ms. Kumar).

Evidence for differences between individual and social forms of engagement are evident in our study, as described in the Results. These findings concur with preliminary indicators of social-affective and social-cognitive engagement found by Fredricks and colleagues (2019) and provide evidence of a social-behavioral dimension (e.g., students assigning tasks to teammates vs. trying to do all tasks themselves). Thus, we argue that a six-dimension conception of engagement is more apt than a four-dimension framework (i.e., individual-affective, individual-behavioral, individual-cognitive, social-affective, social-behavioral, and social-cognitive, rather than affective, behavioral, cognitive, and social). However, additional quantitative work is needed to test the validity of the six-dimensional model suggested by primarily qualitative work to date.

6.3 | Implications for Self-Efficacy Theory

Though self-efficacy theory has existed for over 40 years, there is still need for research in certain ways, such as work with finer gain sizes for data generation, with more racially/ethnically and culturally and linguistically diverse participants, in contexts with meaningful use of educational technology (Schunk & DiBenedetto, 2016, 2020). Our study addresses those needs, in part as detailed in the Methods section, and further detailed below.

6.3.1 | Through affective processes for anxiety management

Whereas the pre-/post-survey results indicated no statistically significant difference in anxiety levels, our finer-grained data generated from observations and interviews suggests that the retaining of the null hypothesis was due to counter-balancing factors, either of which alone might have resulted in statistically significant increases or decreases in anxiety. To mitigate the risk of a new experience (i.e., a formal approach to inventing) increasing anxiety due to unfamiliarity and uncertainty, we argue that at least two considerations of social infrastructure were crucial. First, the team-based approach to the project enabled students to support and encourage each other through difficult situations, acting as "anxiety palliatives" (Bandura, 1993, p. 134). This peer-peer support developed capacity for dealing with anxiety-inducing experiences (at least in inventing, and potentially in similar project-based learning), helping youth to "direct their efforts at resolving problems", thereby strengthening their resilience (Bandura, 1993, p. 134). Second, the teacher-moderated Gallery Walk emphasized that everyone can learn from mistakes and errors, and that constructive criticism need not be a personal attack, but rather an opportunity for growth. We encourage educational designers to include these considerations during design-based planning, implementation, and reflection on instructional units.

6.3.2 | Through cognitive processes for comparison

The aforementioned team-based structure and Gallery Walk activity presented opportunities for youth to compare themselves with others, as facilitated by both peers and teachers. In many cases, youth defined errors as their device performing more poorly than their peers' devices. Fortunately inventing embraces "errors as a natural part of an acquisition process" (Bandura, 1993, p. 120), meaning that comparing can be a generative rather than discouraging dynamic. One potential design improvement already mentioned in the "Conceptions of learning and knowledge" section is the expansion of prizes or other recognition. If students were presented with additional criteria for success (e.g., efficiency, aesthetics, communication/marketing), they might then make more comparisons *with themselves*, that is, their *past* selves. In other words, they would focus "more [on] personal improvement than comparison against the achievement of others" (Bandura, 1993, p. 120). And while some interpersonal comparison might be unavoidable, the *intra*personal comparison might be more appropriate for their own zones of proximal development (Vygotsky, 1978). In a similar way, the aforementioned examples of younger and more diverse inventors might present more reasonable and generative comparisons, relative to older and more homogenous inventors (Thomas Edison, Albert Einstein, etc.).

6.3.3 | Through cognitive processes for ability

With such a close assessment (Ruiz-Primo et al., 2002) of development through self-efficacy via cognitive processes for ability, it is no surprise that there were statistically significant increases, especially for the items more targeted to science and engineering domains, which were of primary concern to the participating teachers (see Table 2.8 for details, including effect sizes). As data from observations, student interviews, and teacher interviews suggests, despite the contest-oriented nature of the project, both students and teachers alike were still focused on quiz and test grades as a measure of ability. Though we acknowledge that traditional "pencil-and-paper" assessments can be *one* useful measure of ability, we posit that posters, presentations, and patent-writing can provide additional opportunities for students to express their learning. These opportunities can leverage engagement, equity, and diversity to expand what "counts" as ability in technological inventing, as well as other disciplines related to science and engineering (Rodriguez, 2015). Another opportunity to expand notions of ability was through peer feedback, which can provide several if not dozens of questions and comments, many more than would be practical for one teacher to provide. While none of these design considerations are particularly new to educational design, invention education does provide a framework that promotes their inclusion to ensure that contrivances are useful, unique, reduced to practice, and non-trivial (Committee for the Study of Invention, 2004; Invention Education Research Group, 2019).

6.4 | Limitations and Future Directions

This study is somewhat limited due to not yet having longer-term follow-up interviews, an especially important consideration for self-efficacy through selection processes. Despite our concerning finding of initial decreases in career intentionality, we are encouraged by other studies showing that continued exposure to, and engagement in, STEM activities can support youths' self-efficacy and persistence in STEM (Aschbacher et al., 2010; Blustein et al., 2013; Mark et al., 2014). In a broader sense, the study is situated in the specific context of one middle school in Mills City. Although the setting is racially/ethnically and culturally and linguistically diverse, it is nonetheless not representative of all learning environments, so our findings might not readily transfer to additional learning environments.

It is with those limitations in mind that we continue our cultural psychology approach to design-based research (P. Bell, 2004), revising our educational design with each subsequent iteration, in conversation with colleagues in the field of STEM education in general and invention education in particular. Overall, we aim to remain "humble and accountable to design" (Anderson & Shattuck, 2012, p. 17), as we work to extend useful theories related to social infrastructure, student engagement, and self-efficacy.

6.5 | Conclusion

The present study, as building upon and extending similar studies, demonstrates the promise of invention education for designing "energetic, yet relaxed" learning environments that can support students' engagement in meaningful technological inventing, with longer-term development of self-efficacy in inventing and related disciplines. Especially if care is taken to preserve student agency in identifying and empathizing with relevant users or beneficiaries, inventing can expand what "counts" as science and user-centered engineering while facilitating connections with disciplines in the arts and humanities. We hope that this paper provides useful design considerations that can help invention education transition from its more out-of-school-time beginnings into more in-school-time implementations, to ensure equitable access and engagement for each learner and all learners, especially those who have been historically marginalized from science and engineering. Ultimately, educational design can help to take inventing, science, and user-centered engineering from, in the words of Paz, "not my thing" to "my thing".

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Section III (Paper #2), "'Magic' or 'maybe ... other years': Designing for Young Adolescents' Engagement and Self-efficacy in an Invention Camp"

ABSTRACT: Student engagement is a central concept for educational practitioners, researchers, and evaluators, and is especially important for learners historically marginalized in science. Design-oriented projects in the field of invention education show potential for promoting equitable engagement, in part by building upon learners' social and cultural backgrounds and experiences. However, the relationship between more social and more individual conceptions of student engagement is not yet well understood. We took a cultural psychology approach to design-based research for planning, implementing, and analysing a five-day camp in the Northeast US, wherein grades 6-8 students invented an electronic door and a free-choice invention. The present mixed-methods case study for convergence revealed some statistically significant changes in engagement and self-efficacy for inventing, which qualitative analyses suggest were related to campers' self-efficacy expressed through cognitive processes about ability with technology, campers' perceived agency for inter- and trans-disciplinary approaches to inventing, and the camp's social infrastructure for student participation. Further, we found evidence to differentiate individual and social levels of affective/emotional, behavioural, and cognitive engagement, supporting a proposed six-part model over previous three- and four-part models. We conclude with conjectures about relationships between the camp's enactment, learning processes, and outcomes, providing an educational model that could

be useful for the design of similar environments for user- or activity-centred design and invention projects.

Keywords: student engagement; affective domain; design study; K-12

Introduction

Student engagement is valued by educational practitioners, researchers, and evaluators, both as a predictor of long-term success and as an outcome itself, and as a way to connect students with the general public (Christenson et al., 2012; McKinnon & Vos, 2015; Olitsky & Milne, 2012). One way to promote student engagement is through inventing and user- or activity-centred design, which can increase youth identification with and participation in science-related programs (Invention Education Research Group, 2019; Zimmerman & Bell, 2014). We still need to know more about how youth participate in invention- and design-focused camps, clubs, classes, and other collaborative learning spaces around the world, in order to ensure that opportunities to engage are initiated and sustained in equitable ways (Cowie et al., 2011; DeWitt & Archer, 2017; Thiry et al., 2017).

This paper centres on a five-day vacation camp with racially/ethnically, culturally, and linguistically diverse youth in grades 6-8 during February of 2019, for inventing electronic doors and free-choice inventions in the Northeast US (Massachusetts Institute of Technology [MIT], 2016). The camp was the third iteration of design-based research using a *cultural psychology* approach (P. Bell, 2004), wherein the camp was considered to be its own microculture of individual and social dynamics, as situated in broader developmental contexts (Bronfenbrenner, 1993). Further, the camp's design was influenced by two previous classroom-based interventions during the school year (Zhang et al., 2021). For this particular study, the research team focused, with respect to inventing, on youths' affective and social engagement (Fredricks, Wang, et al., 2016) and their self-efficacy (Bandura, 1993), as well as relationships between engagement and self-efficacy (Schunk & Mullen, 2012). Specifically, we addressed the research questions,

1. During a grades 6-8 invention camp, how did youth affectively and socially engage in practices of inventing?
2. How did engagement in practices support campers' expression of self-efficacy?
3. Which educational design considerations interacted with campers' engagement and practices?

Conceptual Framework

Self-efficacy Theory

This work is informed by the social-cognitive approach of self-efficacy theory, related to persons' 'belief in their abilities to produce given attainments' (Bandura, 2006, p. 307). Despite the individual nature of the term, self-efficacy exists in a '*triadic reciprocity*' of 'personal factors…., behaviours, and social/environmental factors' (Schunk & Mullen, 2012, p. 221; emphasis in original). In fact, researchers have developed *collective* notions of self-efficacy, sometimes differentiated between dialectics of teachers/instructors with students/learners (Schunk & DiBenedetto, 2016).

In a variety of settings, self-efficacy has shown both explanatory and predictive value, related to concepts such as motivation, educational attainment (or dropout), participation (or avoidance), and student engagement (or disaffection) (Schunk & DiBenedetto, 2016). Because self-efficacy is context-dependent (Bandura, 2006), we used a customized questionnaire as will be detailed in the Methods section.

Student Engagement

Engagement in general has been studied for at least hundreds of years, with student engagement in particular rising in the 1980's through school-dropout studies (Christenson et al., 2012). Recently, student engagement has been more positively framed in its relation to identity, interest, and motivation, often through various dimensions, and as bridging in- and out-of-school learning (McKinnon & Vos, 2015). One popular model (Christenson et al., 2012) is that of Fredricks and colleagues (Fredricks et al., 2004; Fredricks, Wang, et al., 2016), with dimensions of affective/emotional, behavioural, cognitive, and social engagement, roughly relating to feeling, doing, [meta-]thinking, and interacting, respectively. More work is needed to distinguish whether social engagement is its own dimension, or if it interfaces with the other three dimensions to make a six-dimension model (Fredricks, Wang, et al., 2016). The current study focuses on affective engagement, in both individual and social ways.

Practices of Inventing

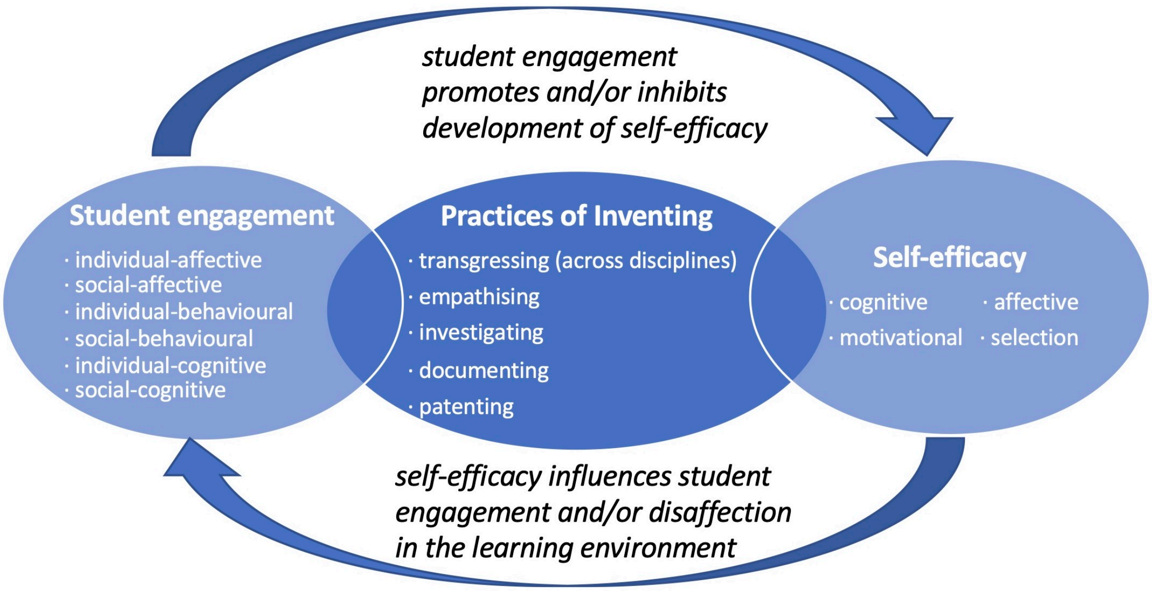
Because the project explicitly includes various 'historical, social, cultural, and ethical aspects… better treated at the level of curriculum design' (National Research Council, 2012, p. 248), we focused on invention practices that might supplement the engineering design practices of the Next Generation Science Standards (NGSS; NGSS Lead States, 2013), to which the participating district's in-school-time curriculum is well-aligned. Practices of inventing were considered both inductively and deductively. For deductive approaches, we used concepts from invention education (Invention Education Research Group, 2019), as manifested in the *Types of Team Members* (TTM) framework of the Lemelson-MIT JV InvenTeams program (Massachusetts Institute of Technology [MIT], 2016). Towards the beginning of the intervention, students self-ranked their affinity with *Doodling* (diagramming, drawing, sketching), *Organizing* (artifacts, persons, tasks, tools), *Talking* (especially as public oration), or *Tinkering* (hands-on manipulation of materials and tools). However, these roles were not fixed; for example, the second-to-last day of the camp had much Tinkering as campers finalized their prototypes, and the last day of camp had much Talking during the community Showcase of student work. In addition to roles of the TTM framework, we considered five invention practices of *transgressing (across disciplines); empathising; investigating* (which also includes experimenting and thinking); *documenting*; and *patenting* (Massachusetts Institute of Technology [MIT], 2016).

Connections within the Conceptual Framework

We view self-efficacy and student engagement as mutually promoting or inhibiting, and both are situated in students' practices of inventing. This approach is consistent with the multifaceted nature of student engagement, which can be viewed as a predictor, mediator, moderator, or outcome (Christenson et al., 2012). Figure 3.1 illustrates the connectedness of the conceptual framework.

Figure 3.1

Relationships between Components of Conceptual Framework



Literature Review

The current study, as well as its review of the literature, focuses on youth aged 10-15, a particularly sensitive period for engagement and interest in fields related to technological inventing, namely science and design (Dabney et al., 2012; Santrock, 2007).

Conceptual Work on Student Engagement in Science, Engineering, and Design

Conceptions of student engagement vary across timescales and contexts (Polman & Hope, 2014; Zimmerman & Bell, 2014). For example, studies can range from shorter-term *momentary engagement profiles* (Schmidt et al., 2018) to longer-term *active prolonged engagement* (Humphrey, T., & Gutwill, 2017). Further, research and evaluation range from cohort-, organization-, and society-level orientations, such as the context-based model of *educational*, *institutional*, and *democratic* engagement from Lewenstein and colleagues through a UK-US partnership (Lewenstein & Philips, 2019). The current study tends towards the shorter-term and smaller-scale approaches to engagement, extending to camps the previous work mostly done in classrooms and museums (Riedinger & McGinnis, 2017). Our ongoing research-practice partnership includes more medium-term and medium-scale components (Zhang et al., 2021).

Empirical Work on Student Engagement in Science, Engineering, and Design

Mindful of the relatively short, five-day duration of the Winter Vacation Camp[2], this review focuses on camps of similar lengths. Previous work provides evidence that four- and five-day interventions can have substantial success considering their relatively short durations (Maiorca et al., 2021; Mangan et al., 2019; Riedinger & McGinnis, 2017).

Around the world, camps can be out-of-school-time spaces that both complement and supplement in-school-time learning (Bevan et al., 2010). For example, more complementary functions include the introduction or reinforcement of content knowledge (Mangan et al., 2019), whereas more supplementary roles include the development of interest, career intentionality, science identity, and awareness of indigenous approaches to science (Cheeptham et al., 2020; Maiorca et al., 2021; Renninger & Bachrach, 2015; Riedinger & McGinnis, 2017).

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[2] Unless otherwise noted, all program, participant, city, and school/district names are pseudonyms. Care has been taken to preserve cultural and linguistic connotations, while still maintaining anonymity.

In a study that emphasized content knowledge, Mangan and colleagues (2019) found that incorporating both music and movements into songs about planetary order and lunar phases resulted in improved performance on a 10-item pre- and post-test, based on work over four years with 288 rising 5th-8th graders in a summer camp at James Madison University in Virginia, USA. The authors noted large effect sizes for items sequencing the phases of Earth's moon, as well as medium-to-large effect sizes for the order of planets in our solar system. They argue that incorporating both music and movement into activities can improve knowledge acquisition and retention.

Shifting now from more cognitive to more affective and social domains, we note previous work in camps that relate to interest, identity, and careers. Maiorca and colleagues (2021) shared findings from a camp in the US at the University of Kentucky, wherein 1,000-plus youth in grades 5-8 participated in activities related to robotics and biomedicine. Based on questionnaires from roughly 50% of the campers and interviews with approximately 40% of the campers, the researchers found a small-to-medium effect size (Cohen's $d = 0.49$) for increases in self-efficacy towards STEM careers, as supported by role models, relevance, and empathy in the camp. Similar themes were reported by Riedinger and McGinnis (2017), who performed finer-grained analyses that delved into processes of positioning, discourse, and performance, as related to development of campers' science identities. Drawing from a sample of middle schoolers chosen for their 'ability to communicate effectively' (p. 84), one African American female, five White female, and three White male campers used 'everyday language' during activities like 'animal collection', enabling them to author identities in ways they did not encounter with ‘classroom’ science (p. 97). Riedinger and McGinnis argue that focusing on *peer-to-peer* conversation can provide insight into identity development, a contribution that builds on previous work with families using *adult-and-youth* conversation (Bricker & Bell, 2014).

Methods

Methodology

To study how youths’ affective and social engagement in practices of inventing facilitate the development of their self-efficacy towards inventing, we took a *cultural psychology* approach to design-based research (P. Bell, 2004). This approach considered the camp as its own microculture, with individual and collective dynamics, as situated in broader developmental contexts (Bronfenbrenner, 1993).

Setting and Participants

The 2019 Winter Vacation Camp took place at one of the two grades 6-8 public middle schools in Mills City, an urban-ring city in the Northeast US. The present-day demographics of middle-school students in Mills City are diverse in terms of race/ethnicity, language, gender, national origin, and socioeconomic status. In 2019, our recruitment efforts in yielded much more interest from self-identified male youth than for their female or non-binary peers, as reflected in Table 3.1. Based on feedback from previous camps, we believe that a main reason for the gendered differences in interest was the content area of the curriculum.

Table 3.1

Racial/Ethnic, Gender, & Language Demographics from the 2019 Winter Vacation Camp

	African-American	Asian	Caribbean	Hispanic/ Latinx	Multi-racial	White	Prefer not to say / blank
Female (8)	0	2^{E}	1^{E}	3^{S}	1^{E}	1^{E}	0
Male (25)	1^{E}	4^{E}	0	$1^{E} + 4^{S}$	2^{E}	11^{E}	2^{E}

Notes. A superscript 'E' indicates an application completed in English, and a superscript 'S' indicates an application completed in Spanish. Used with permission from Jackson and Bendiksen (2020).

Planned and Enacted Curriculum

In the Winter Vacation Camp, we designed the learning environment to promote social and affective engagement, through both invention-focused activities as well as visits from professional designers and community members. In these ways, we sought to foster multiple dimensions of engagement through several pathways.

We adapted the *U Control* curriculum by the Lemelson-MIT JV InvenTeams program (Massachusetts Institute of Technology [MIT], 2016). The two main projects of the curriculum are (1) designing and constructing an electric door; and (2) creating plans for, and perhaps a prototype of, a free-choice invention. Though the curriculum calls for all students building doors of identical dimensions, we allowed for doors between roughly half and twice the size of specifications. Thus, some campers designed doors for small pets (~half-size), while other campers designed doors for younger siblings (~double-size). An overview of the curriculum is shown in Table 3.2, and student artifacts are shown in Figure 3.2.

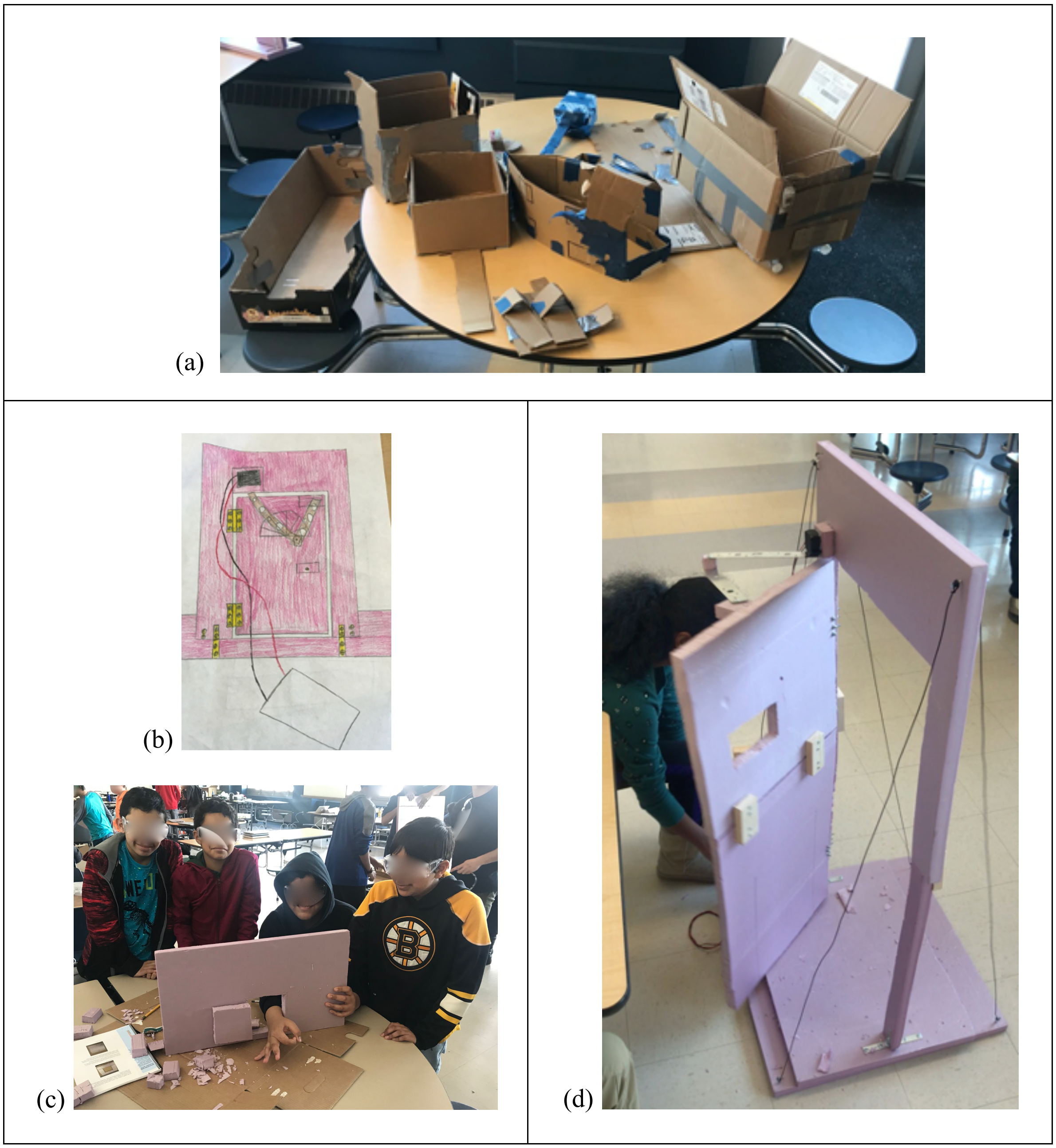
Table 3.2

Curriculum Design for 'Winter Vacation Camp (WVC)'

Day	Topics	Domains	Indiv./Coop.
1	self-introductions, incl. personal histories as inventors	design	individual
	intro to inventing, incl. rapid prototyping (Figure 2.2a)		cooperative
	simple machines: definitions, advantages/disadvantages, and hands-on activities	natural science	individual
2	design of doors: common geometries and mechanisms	design	
	assembly of doors: using foamboard, utility knives, frames, brackets, hinges, screws, etc.		cooperative
3	motors & circuits: principles of function and operation	natural science	individual
	controlling motors: hands-on, with electrical 'breadboards'		cooperative
	levers: principles, with a focus on mechanical advantage		individual
	free-choice inventing, incl. group brainstorming	design	cooperative
4	start final products (both electric doors *and* free-choice inventions)		
	Videoconference #1: professional inventor		
	videoconference #2: attorney for Intellectual Property (IP)		
	peer-review, then continue products		
5	complete products & product-descriptions: electric doors, with supporting posters, slideshows, videos, or pamphlets		
	'Invention Exhibition': public showcase		

Figure 3.2

Photos from the Winter Vacation Camp (WVC). From top to bottom: (a) rapid prototyping; (b) drawing of door; (c) completed door with size halved from instructions; (d) completed door with size doubled from instructions



Research Design

Overall Design

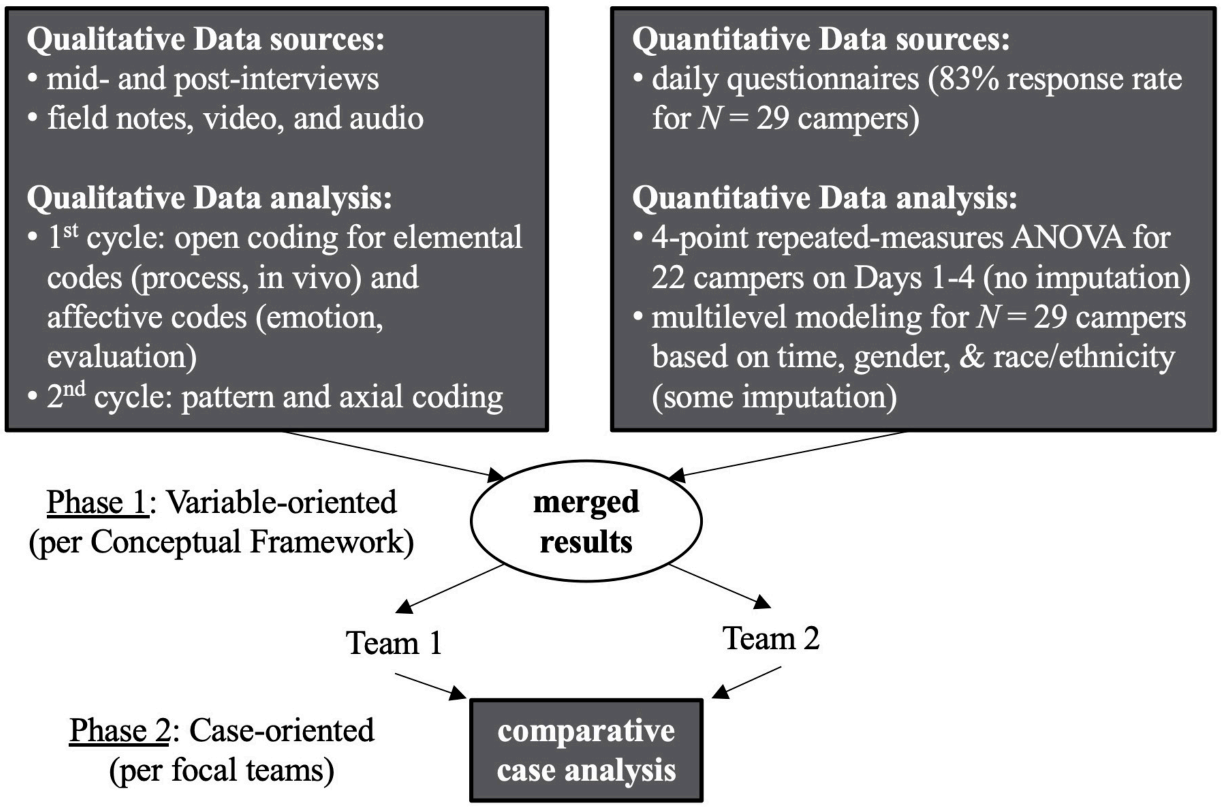
We conducted a sequential mixed methods case study for explanation (Creswell & Plano Clark, 2018), as shown in Figure 3.3. First, we studied the entire camp through pre- and post-interviews, observations (field notes, plus some audio and/or video recordings), and daily questionnaires. Then, we chose two focal-teams, purposefully sampled both for convenience (completed permission forms) and for maximal variation (race/ethnicity, gender, and linguistic background). Whereas observations on the first day of the camp considered all campers, the observations of days 2-5 centred on these two focal teams.

Data Sourcing

Each of our three main data sources (interviews, questionnaires, and observations) closely aligned with two or three parts of our conceptual framework (engagement, self-efficacy, and practices), as summarized in Table 3.3. Interviews focused on engagement and practices, with 7th and 8th graders being asked about practices from a similar project in-school-time (Zhang et al., 2021). Questionnaires for all five days included eight, 7-point Likert-style items on engagement and self-efficacy, with students potentially mentioning practices in one open-ended prompt ('What knowledge and skills did you use from outside camp today?'). We chose a 7-point scale due to poor performance of 3- and 5-point scales (Bandura, 2006) during the preceding two camps. Questionnaires for Days 2-5 also had five, 4-point items related to invention practices via the Types of Team Members framework (Doodling, Organizing, Talking, Tinkering, or 'Something Else' /

Figure 3.3

Research Design: Mixed Methods Case Study for Convergence (Creswell & Plano Clark, 2018)



almost always, often, sometimes, or rarely). Observation protocols were focused on engagement and practices, though evidence of self-efficacy was sometimes noted by participant-observers or evident in audio and video recordings. All protocols are available in the Appendices.

Data Analysis

In Phase 1 of data analysis we performed variable-oriented analyses (Miles et al., 2014). For qualitative analyses, our first round of coding was open coding for elemental

Table 3.3

Alignment of Data Sourcing with Conceptual Framework

	Interviews			Questionnaires			Obser-vations
	Pre	Mid	Post	Pre	Mid	Post	
affective engagement	+	-	+	+	+	+	+
behavioural engagement	+	-	+	+	+	+	+
cognitive engagement	+	-	+	+	+	+	+
social engagement	+	+	+	+	+	+	+
self-efficacy	-	-	-	+	+	+	-
practices of inventing	7-8	+	+	+	+	+	+

Notes. '+' = a target of the instrument, '-' = not explicitly targeted, and '7-8' = for 7th and 8th graders only.

codes (process and in vivo) and affective codes (emotion and evaluation) (Saldaña, 2009). The process coding primarily related to developing self-efficacy through practices of inventing; the emotion and evaluation coding directly connect with campers' affective engagement; and the in vivo coding recognizes that youths' practices are socially constructed phenomena that are situated in proximal, distal, and temporal developmental contexts (Bronfenbrenner, 1993). To better understand the relationships between educational design and our concepts of interest, we leveraged Bielaczyc's (2006) Social Infrastructure Framework (SIF). Of the 14 design considerations in the SIF, we found three to be particularly salient, which we coded as epistemology, student-participation-structures, and teacher-participation-structures. Our second round of coding was for pattern and axial codes (Saldaña, 2009), as we explored connections between parts of our conceptual framework.

For quantitative analyses of Phase 1, we first used multilevel modelling (Raudenbush & Bryk, 2002) to account for missing data in the 29 campers who completed at least two questionnaires (overall response rate = 83%). This modelling was based on time (five days of the camp), gender (female/male), and dichotomized race/ethnicity (student of colour or white student). Though these analyses did result in some statistically significant findings (see Results section), we also ran a four-point repeated-measures ANOVA for the 22 campers who completed questionnaires on each of Days 1-4 of the camp (response rate of 100%). These two different approaches, considered together, provide a deeper and more nuanced understanding of campers' self-reported lived experiences (Creswell & Plano Clark, 2018).

After Phase 1's variable-oriented analyses, in Phase 2 we conducted case-oriented analyses (Miles et al., 2014) for each of the two focal teams. We performed cross-case analysis of emergent themes, triangulating data from interviews, observations, and questionnaires. The final code list is shown in Table 3.4.

Table 3.4

Final Code List for Qualitative Data

engagement	individual-affective; social-affective; individual-behavioural; social-behavioural; individual-cognitive; social-cognitive; ***disaffected*; *re-engaged; individual⇔social; school⇔camp;***
self-efficacy	cognitive-ability; cognitive-comparison; cognitive-controllability; cognitive-feedback; motivation-challenge; motivation-disequilibrium; motivation-reaction; selection-career; selection-formal; selection-informal; ***ability⇔control; ability⇔selection***
invention practices	transgressing (disciplines); empathising; investigating; documenting; patenting; ***transgressing⇔roles; transgressing⇔social-sciences***
Social Infrastructure Framework	epistemology; student-p-s; teacher-p-s; Doodler; Organizer; Talker; Tinkerer; ***p-s-balanced; p-s-imbalanced; p-s-fluid; p-s-static; p-s-gendered-dominant; p-s-gendered-resistant; p-s-usefulness***

Note. Codes in ***bold italics*** are inductive codes. ‘p-s’ denotes participation-structures.

Details about Focal Teams

We chose focal teams based on convenience sampling (for returned permission forms) and maximal variation (based on available demographics) (Creswell & Plano Clark, 2018). Each team had a participant-observer, who took field notes during group work. Demographics and reasons for applying to the camp are listed in Table 3.5 for the two focal teams.

Results

We focused on social and affective engagement for the one-week invention camp, given engagement's central role in outcomes such as self-efficacy, academic attainment, and career selection (Christenson et al., 2012; Schunk & Mullen, 2012). From an educational design perspective, forms of engagement can be viewed as *mediating processes*, connecting the *embodiment* of a designed learning environment with *intervention outcomes* desired by designers (Sandoval, 2014). In this section we describe the lower-inference phenomena related to mediating processes. We situate engagement processes in practices of inventing, especially those of transgressing (across disciplines), empathising, and investigating (Massachusetts Institute of Technology [MIT], 2016), as we saw little evidence of documenting or patenting. The higher-inference aspects of *embodiment* and *intervention outcomes* will be addressed in the Discussion section.

We will present full-camp quantitative findings first, in the spirit of a whole-to-part analysis (Erickson, 2006). Then the qualitative findings will proceed in a chronological and phenomenological fashion, consistent with considering the camp and

Table 3.5

Background Information for Two Focal Teams, based on Camp Application-forms

	Name	Race / Ethnicity	Gender	Grade	School	Language of application	Reasons for wanting to participate in the camp
Team 1	Sara	Latinx	female	6	Central	*español*	'I am interested in technology & electrical engineering. I would like to learn more.'
	Edith	Latinx	female	8	Northwest	*español*	'I would like to learn more about *cosas electrónicas* (electrical things/devices/topics).'
	Doug	white	male	8	Northwest	English	'…so I can learn how electricity can open a door and have fun working with classmates being creative.'
	Adam	Asian-American	male	8	Saint Anthony's	English	'Science is a favourite subject of mine! I love to design, build, and experiment….'
Team 2	Samuel	Latinx	male	8	Central	*español*	'It seems interesting to me, to learn the mechanics of how an electronic door works.'
	Pedro	Latinx	male	8	Central	*español*	'Imma (I'm going to) learn how to make a door for my birds.'
	Omor	Asian-American	male	6	Central	English	'I would like to learn about circuits, coding, and building. I really like to think of new invention ideas and then how to market it…. My favourite summer camp is [invention camp]….'
	Emir	Asian-American	male	6	Central	English	'I am interested in build[ing] new stuff.'

Note. Spanish-language responses have been translated when loss of meaning is minimal.

teams as their own microcultures, per the cultural psychology approach to design-based research (P. Bell, 2004). The qualitative findings will start with each of the two focal teams separately, followed by a cross-team comparison. For the focal teams, findings from questionnaires will be framed in a *quantitative-as-qualitative* manner, emphasizing increases, decreases, or constants in self-reported measures, as opposed to magnitudes thereof (Creswell & Plano Clark, 2018). Throughout this section, we will note connections between engagement, self-efficacy, invention practices, and social infrastructure.

Full-camp Quantitative Data

We conducted a four-point, repeated-measures ANOVA for the 22 campers who completed surveys on Days 1-4. The only statistically significant changes at the $\alpha = .05$ level were for self-efficacy in '[using] electrical circuits to change how a motor performs' (Day 1 to Days 2/3/4, p of .034, .001, and <.001, respectively); behavioural engagement as '[staying] focused in vacation camp' (Day 2 to Day 4, $p = .015$); behavioural engagement *relative to school*, as '[paying] more attention in vacation camp than I do in school science' (Day 1 to Day 2/3/4, p of .003, <.001, and .017, respectively); and the role of Tinkering (Day 2 to Day 3, $p = .044$). These changes are logical given the curricular scope and sequence of the camp (see Table 3.2), including construction being started on Day 2 of the camp and the majority of circuits-based activities taking place on Day 3 of the camp. The lack of additional statistically significant changes makes sense given the short duration of the camp. For example, it generally takes more time to see shifts in inventing-related attitudes (Invention Education Research Group, 2019) for items like ‘I can work in MANY different ways on *my own* invention project’ and ‘I can work in MANY different ways as part of an invention *team*’; see Appendix 2 for the complete questionnaire).

In an analysis that used imputation for missing data amongst the 29 campers who completed at least two self-assessments, we completed multilevel modelling (Raudenbush & Bryk, 2002) for time (Day of camp), gender (female/male), and dichotomized race (student of colour or white student). This analysis resulted in statistically significant growth in self-efficacy for seven of eight items, with gender not found as a significant predictor. One of the eight items showed a narrowing of an initial gap between students of colour and white students, though the gap was not fully closed. Further details may be found in Jackson and Bendiksen (2020).

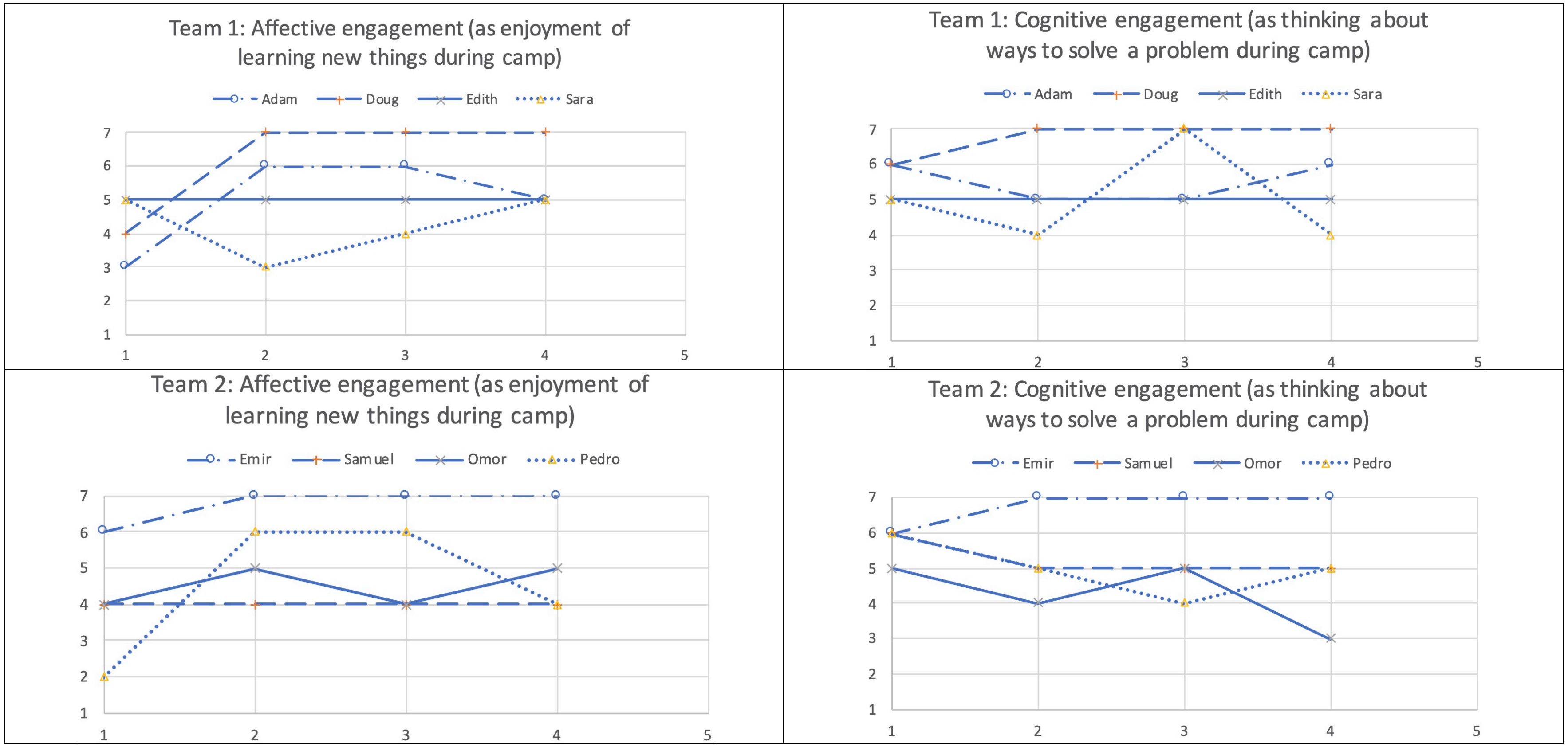
Affordances and limitations of these analyses will be addressed in the Discussion section. For now, we proceed to quantitative-as-qualitative and qualitative findings (Creswell & Plano Clark, 2018), to add nuance to these full-camp quantitative findings and arrive at deeper understandings of campers' lived experiences.

Focal-team Quantitative Data

Selected summary graphs of affective and cognitive engagement for each focal team are shown in Figure 3.4. Also, selected charts for role-changing are displayed in Figure 3.5. We present these Figures before the narratives to provide a general sense of intra-team dynamics, which we address more specifically in the narratives below.

Figure 3.4

Affective and Cognitive Engagement as Self-reported by Campers in Team 1 and Team 2



Note. Each horizontal axis represents the Day of the camp. Each vertical axis represents the Likert-style response space from 'strongly *dis*agree' (1) through 'strongly agree' (7).

Figure 3.5

Fluidity of Inventing Roles for Team 1 and Team 2, per Types of Team Members Framework

Note. Team 2 showed greater fluidity in their roles, as supported by the greater number of transecting lines (4 vs. 1). Each horizontal axis represents the Day of the camp. Each vertical axis represents the response space of ‘rarely’, ‘sometimes’, ‘often’, or ‘almost always’ (from 1-4, respectively).

Team 1 Narrative (Edith, Sara, Adam, and Doug): 'hablar más', 'maybe to the other years'

The story of Team 1's camp begins *before* the camp. Edith and Sara entered the camp cautiously, revealing in their joint post-interview that 'because it was [their] first time in camp' they did not feel that they could choose to be a Tinkerer. On the other hand, Doug entered confidently, in part based on his experience 'build[ing] toolboxes and benches' with his uncle. In other words, Doug's engagement was primed by his previous experiences through cognitive self-efficacy for ability. Inversely, Edith and Sara's opportunity to engage was restricted through cognitive self-efficacy for controllability of the environment, which was only partially offset by near-peers' and adults' efforts to foster more inter-group talking ('*hablar más*'), as was evident during the course of the camp.

Early in the camp, Doug took the lead on Tinkering, while Adam performed both Tinkering and Organizing. Edith and Sara shared in post-interviews that they would have liked to do Tinkering, but they were static in Doodling. As noted during a mid-interview with a near-peer counsellor, 'kinda just the Tinkerer had something to do'. So, Edith and Sara mostly watched (disaffected) while Adam and Doug behaviourally engaged. During this time, data generated from video (Erickson, 2006) suggest that near-peer counsellors primarily supported the engagement of the two boys, and talked little with the two girls (i.e., they would have done better to 'hablar más', or speak more, with the two girls). In this phase of the camp and in subsequent phases, Team 1 exhibited the invention practice of investigating, which aligns well with the role of Tinkering. Notably absent were transgressing and empathising, which could have involved Organizing more, and also documenting and patenting, which could have encouraged more engagement from via Doodling and Talking. Field notes indicate that Edith and Sara would have liked to make a door for their 5-year-old cousin, but Team 1's final product was a reproduction of the example from the curriculum, one that is too small for a 5-year-old (i.e., an opening of 30 cm x 30 cm).

Towards the middle of the camp, interventions from adults supported the individual- and social-behavioural engagement of Edith and Sara. One participant-observer and two adult co-advisors spoke directly with Edith and Sara, resulting in increased individual contributions to Doodling and social contributions to Tinkering. For example, Edith and Sara worked in parallel on completing diagrams of their final design (see Figure 3.2b). Also, each took a turn at holding some foamboard and fastening brackets to the foamboard. During these sequences they exhibited more erect posture and a more focused gaze, suggestive of increased individual-affective engagement.

By the end of the camp, the individual-behavioural engagement of the four teammates was much more balanced than it was at the beginning of the camp, but still had Adam and Doug engaging more than Edith and Sara. In hindsight, Edith and Sara expressed a wish that adults and youth alike had talked more (*hablar más*) *and* sooner, a desire that will be revisited in the Discussion. As mentioned earlier, increased emphasis on transgressing, empathising, documenting, and patenting could have facilitated engagement, including via talking.

Looking to the future, Edith and Sara stated that they would be more likely to Tinker 'maybe to the other [upcoming] years'. As an 8th grader, Edith had no more opportunities to participate in subsequent editions of this particular camp; however, Sara had two more opportunities, neither of which she applied to. While it is unknown if Edith and Sara did similar camps elsewhere in 2020 or 2021, there is no evidence that the 2019 camp supported their selection self-efficacy in any career, formal, or informal ways.

The Team 1 themes of hablar más (talking more) and 'maybe to the other years' have implications for educational design, as will be detailed in the Discussion. For now, we proceed to Team 2, where students positioned themselves and others as 'gods' amidst group dynamics that worked like 'magic' to facilitate engagement.

Team 2 Narrative (Samuel, Pedro, Omor, and Emir): 'gods' and 'magic'

Entering the camp, two members of Team 2 had developed their cognitive self-efficacy for ability, in similar ways to Doug's development in Team 1. For Pedro, his self-efficacy was developed from an early age (five years old), when he helped his grandpa make a bed, later helped with the assembly of a birdcage, then further strengthened in technology education class (the preceding year-and-a-half of school). For Emir, working with his dad, a 'scrap man' who 'uses a lot of metal', gave Emir 'a lot of skills on how to use tools'. Further, Emir developed his ability with wiring through a toy-train set at home. However, these initially-high levels of cognitive self-efficacy for ability differed in their persistence for Pedro and Emir, as became evident toward the middle of the camp.

Early in the camp, Team 2 attempted to stay close to their designated roles of Emir as Doodler, Pedro as Tinkerer, Omor as Talker, and Samuel as Organizer. However, with little Doodling and Talking at the beginning of the project, both Emir and Omor shifted towards Tinkering. Pedro, who self-described as ‘a god at using this [unknown] tool and hammers’, also engaged in Tinkering at first. Samuel, who one participant-observer noted would ‘go with the flow’, emphasized keeping the materials organized, but did not mention keeping tasks or persons organized. Thus, at first all members of Team 2 were behaviourally engaged, in a variety of individual and social ways (e.g., individually organizing materials vs. socially tinkering with the electronic door). The transition of roles for three of the four teammates was described as ‘magic’ by Pedro in his post-interview. Thus, Pedro showed little cognitive engagement with the Types of Team Members framework, as did Emir, Omor, and Samuel. Compared to Team 1, Team 2 showed more empathising, namely through the door being designed for small pets, with an opening of approximately 10 cm x 10 cm. This design choice likely supported affective engagement, given the enthusiasm for pets that Pedro expressed in mid- and post-interviews.

Towards the middle of the camp, Emir and Omor remained Tinkering and Samuel remained Organizing. However, Pedro got frustrated with wiring, calling it ‘magic’ and describing Emir as a ‘god’ at wiring. In this case, a lack of motivation self-efficacy prompted Pedro to dismiss wiring as something undecipherable, deferring to the greater perceived cognitive self-efficacy of Emir. Thus, being a ‘god’ at some tools did not transfer to Pedro in wiring, nor did the ‘magic’ that had balanced engagement hold when tasks became less familiar.

Near the end of the camp, two very different notions of Talking emerged. Pedro, who had recently decreased his engagement as a Tinkerer, behaviourally engaged in individual ways, ‘talking in general’ and ‘just rambling on with everyone’, including campers outside of his group. On the other hand, Emir recognized a social-cognitive way to engage in Talking, namely to ‘describe it [invention] and make sure people get it [understand it] ‘. In other words, Emir realized that a personal understanding via individual-cognitive engagement was necessary but not sufficient to explain concepts to others (the latter being social-cognitive engagement).

In post-interviews, Team 2 offered few suggestions for future camps, with one exception. Pedro offered the idea of ‘fun things’ such as ‘programming a boat... or modern stuff that kids, like, teenagers would use every day’. When probed for ways to make such a project culturally relevant, Pedro resisted, stated that ‘then there's just different things for everyone’, which ‘would be chaotic’. In terms of engagement, Pedro forwarded the importance of the affective dimension, though he was wary of it becoming behaviourally unwieldy.

Cross-case Findings for Team 1 and Team 2

For both teams, a pre-camp development of self-efficacy for ability supported in-camp individual-behavioural engagement, as seen with Doug, Emir, and Pedro. Such self-efficacy did not, however, foster social-behavioural engagement; in fact, it may have impeded it. During his post-interview, Doug stated that ‘it's best to do what you're better at, and whatever else people are better at, they can do that role, too'. This attitude was shared with Pedro, who engaged in his preferred forms of Tinkering (using hammers and screwdrivers) yet became disaffected during the tasks related to using wires and an electrical prototyping board ('breadboard'). These orientations necessitate counter-measures at the level of educational design, as will be addressed in the Discussion section.

For affective engagement, campers expressed individual engagement via the novelty of the materials, relative to their school science classes. For example, Doug noted that in 'normal [school] science, we used to use just scissors, but [in camp] we used like blades and stuff.' On a more social level, Pedro noted that the camp had 'more freedom', compared to his science classes which are 'not very fun' when group members do not contribute and the teacher checks-in 'every five seconds'. Nonetheless, one near-peer counsellor expressed that the 2019 camp could have been more fun, such as in previous years when the topic was more interesting and the roles were more balanced (building musical instruments, which involved more drawing during the planning phases in particular). Further, the same counsellor noted that free-choice inventing seemed to increase affective engagement, accordingly recommending that more time be allocated to free-choice inventing during future camps.

In terms of cognitive engagement, some can be inferred from increases in self-efficacy scores related to '[using] electrical circuits to change how a motor performs' and '[applying] understanding of electromagnetism to build an electric door'. However, according to a near-peer counsellor, 'they [campers] just followed the instructions in the book', implying a high level of behavioural engagement yet a low level of cognitive engagement. Analysis of pamphlets and slideshows generated for the camp Showcase suggests that some campers cognitively engaged to create thorough artifacts, yet many campers produced minimal or incomplete products. In this case, more emphasis on inventing practices of *documenting* and *patenting* could have promoted cognitive engagement, at least towards the end of the project.

Closing Remarks for Results

In sum, the quantitative findings, when considered alongside the qualitative findings, support a cautious optimism that further interventions could foster youths' self-efficacy, which depends on context and tends to develop over timescales longer than one week (Schunk & DiBenedetto, 2016; Schunk & Mullen, 2012). Engagement shows promise in connecting these longer-term outcomes to shorter-term, more directly observable phenomena, as will be detailed in the Discussion.

Discussion

In this study we examined young adolescents' engagement in invention practices during a vacation camp, especially in affective and social ways and looking towards development of self-efficacy. We found unequal levels of engagement across two focal groups, potentially exacerbated by the 2019 camp's learning activities and participation structures (Bielaczyc, 2006).

In this section we firstly make connections between student engagement and self-efficacy theory (Bandura, 1993; Schunk & Mullen, 2012). Secondly, we leverage the

Social Infrastructure Framework of Bielaczyc (2006) to make theoretical and design conjectures (Sandoval, 2014) in hopes that they will aid the design of camps in Mills City and beyond.

Connections between Student Engagement and Self-efficacy

Previous work has connected self-efficacy and student engagement in a relatively general sense, relying heavily on pre-/post-, self-report designs during in-school-time with predominantly white and Western students (e.g., in Northern and Western Europe, Canada, and the US; Schunk & DiBenedetto, 2016). The current study extends extant scholarship, using data generated from video and audio recordings, field notes, mid-interviews, and mid-surveys for insight into the 'dynamic nature' of developing self-efficacy (Schunk & DiBenedetto, 2016, p. 49). Further, the racially/ethnically, culturally and linguistically, and socioeconomically diverse participants, including those of Asian and Latin American descent, allow for deeper understandings of the influences of students' backgrounds and experiences, especially as related to more collectivist or individualist worldviews (Schunk & DiBenedetto, 2016; Schunk & Mullen, 2012). In sum, this study particularly elaborates the 'social/environmental factors' in the '*triadic reciprocity*' of self-efficacy (Schunk & Mullen, 2012, p. 221; emphasis in original).

Both our qualitative and quantitative analyses suggested that development of self-efficacy, as supported by student engagement, is a non-linear process, in which initial difficulties or re-conceptualizations could result in early decreases that might be followed by later increases (see Figure 3.4). Also, this study shows that development of self-efficacy can manifest differently for students of diverse social and cultural orientations (e.g., varied emphases on utterances vs. gestures). As described by several campers, the out-of-school-time setting had more freedom than in-school-time settings, which could lead to increased or decreased engagement and self-efficacy, depending on within- and between-person dynamics. This particular camp had evidence of more individualistic orientations supporting increased engagement and self-efficacy (e.g., through Tinkering) and evidence that more collectivist approaches could be successful (e.g., through empathising). Our work provides evidence that instructional supports are especially needed towards the beginning and middle of a project, as detailed below.

Design and Theoretical Conjectures

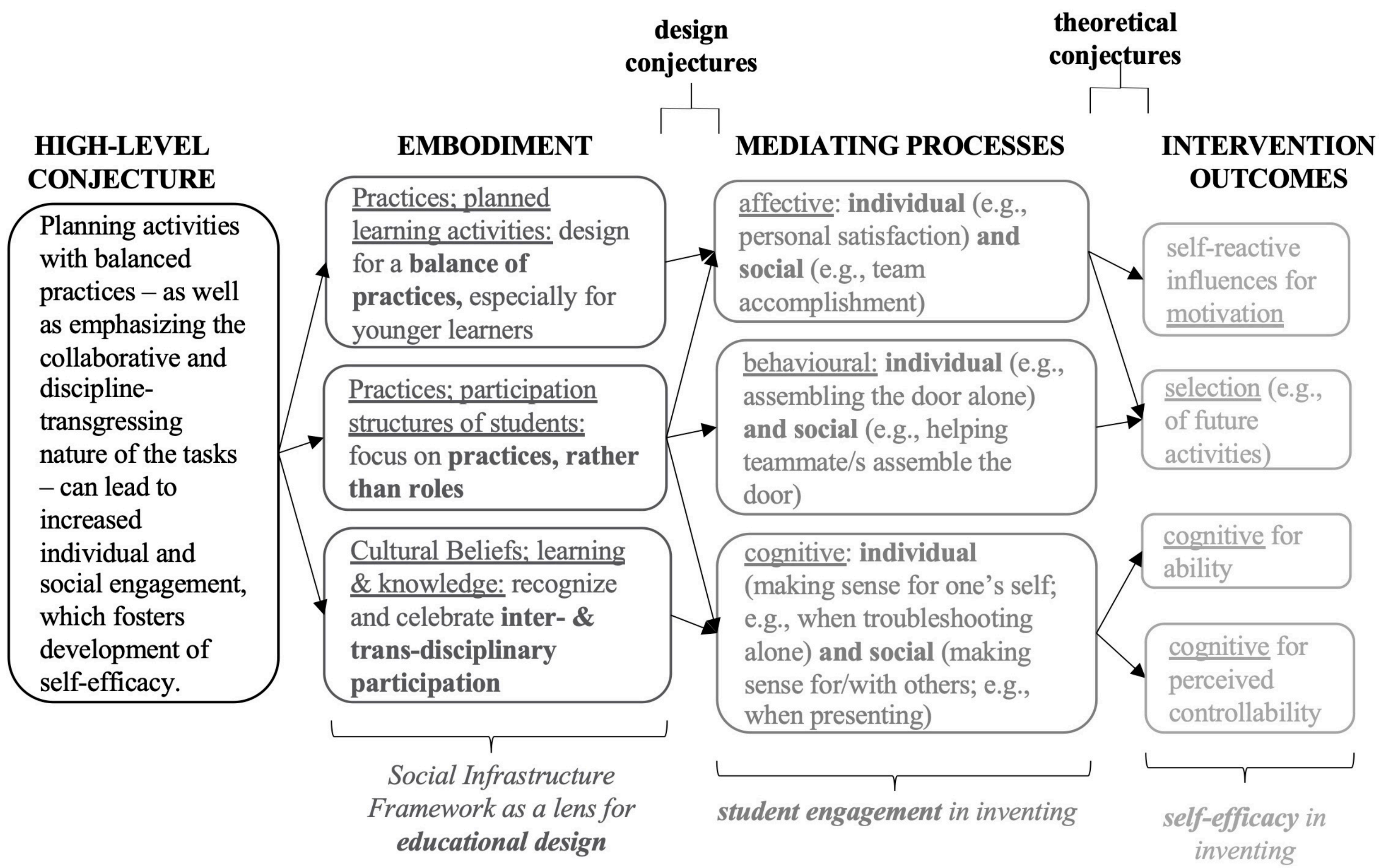
As noted earlier, we viewed forms of student engagement as mediating processes, connecting the embodiment of our educational design with the desired intervention outcomes (Sandoval, 2014). As shown in Figure 3.6, we make design conjectures about how the embodied design facilitated student engagement, followed by theoretical conjectures about how student engagement might support outcomes related to self-efficacy. Overall, we conjecture that more deliberate design for balanced practices, collaboration, and disciplinary transgression will support engagement towards developing self-efficacy.

Design Conjectures

Of the 14 design considerations in the Social Infrastructure Framework by Bielaczyc (2006), our analyses showed the most evidence of *planned learning activities*, *participation structures of students*, and *(Cultural Beliefs about) learning and knowledge.* As noted in the Results section, the 2019 camp was heavy on the role of Tinkerer and the

Figure 3.6

Connections between Design, Enactment, and Outcomes (adapted from Sandoval, 2014)



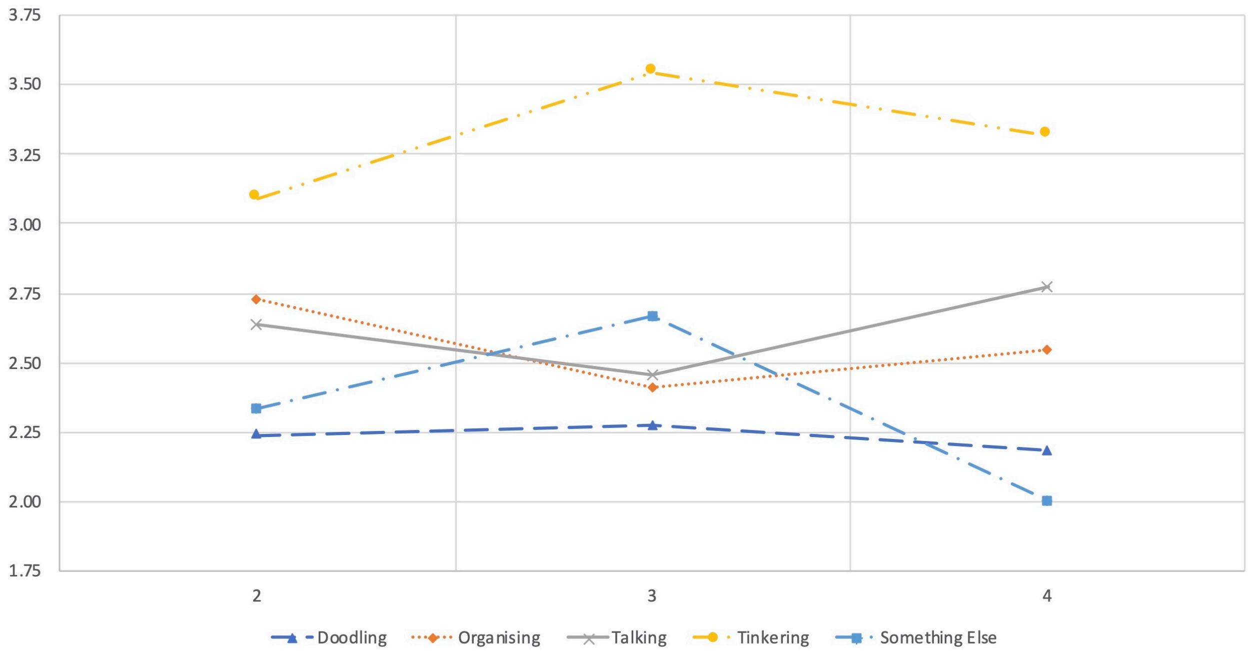
invention practice of investigating. Multiple data sources supported the finding that this imbalance led to affective engagement for those with already-developed cognitive self-efficacy for ability (e.g., Doug, Emir, and Pedro) and disaffection for those newer to the specific topics or to the camp in general (especially Edith and Sara). As attested by a near-peer counsellor who was a camper the previous year, a more interesting topic with more balanced tasks could have supported more balanced engagement (i.e., 2018's planning and construction of musical instruments).

One shift in terminology that might change youths' conceptions of participation would be reframing the roles of Types of Team Members to behaviours. That is, Doodler, Organizer, Talker, and Tinkerer could be renamed as Doodling, Organizing, Talking, and Tinkering, as we did in the daily questionnaire. A metaphor of overlapping waves (Siegler, 1996), such as the one generated from full-camp data (see Figure 3.7), might encourage students to engage in diverse behaviours. In turn, these more balanced behaviours could lead to increased cognitive engagement, as students engage in physical tasks to understand abstract concepts (e.g., building circuits to learn about electrical current). Further, a team-wide distribution of behavioural engagement could at least guard against frustration or boredom (i.e., affective disengagement, or disaffection). Thus, in our conjecture map we show participation structures of students as connected with all forms of engagement (see Figure 3.6).

Earlier we noted increased student engagement during free-choice inventing, as compared to the specific project of an electric door. In addition to the straightforward adjustment of allocating more time for free-choice inventing, we conjecture that promoting increased choice within an existing project might also lead to increased

Figure 3.7

Full-camp Self-reports of Invention Behaviours, Manifesting in Overlapping Waves (Siegler, 1996)



Note. Each horizontal axis represents the Day of the camp. Each vertical axis represents the response space of 'rarely', 'sometimes', 'often', or 'almost always' (from 1-4, respectively). Axes have been truncated to show detail.

engagement. In Team 2, we noted increased engagement due to the door being designed for a pet. Unfortunately, Team 1 did not customize their door, despite Edith and Sara's wishes to construct one for a five-year-old cousin. Perhaps a mandate to *not* replicate the dimensions from the guidebook could foster increased engagement, pre-empting dominant behaviour from more individualistic approaches such as Doug's. These ways of increasing choice could create space for involving disciplines like the arts, humanities, and social sciences, through invention practices of *transgressing (across disciplines)* and *empathising*, as we saw in instances of doors for pets and younger relatives.

Theoretical Conjectures

In addition to design conjectures, we make theoretical conjectures between the mediating processes and intervention outcomes (Sandoval, 2014). Most concretely, we conjecture that behavioural engagement may lead to selection self-efficacy for future activities, as we noted with Doug, Emir, and Pedro. Selection self-efficacy could also be promoted by affective engagement, as fun activities might act as 'triggers for interest and engagement' (Renninger & Bachrach, 2015, p. 58). Affective engagement might also support development through motivation processes of self-efficacy. Recalling Pedro's attraction to hammers and screwdrivers yet aversion to wiring and breadboards, an increased affective engagement might have supported his reaction to the challenges of a skill new to him (wiring).

Our final theoretical conjectures relate to cognitive engagement, which we anticipate as linked to self-efficacy through cognitive processes of ability and perceived controllability. We infer that at least *some* cognitive engagement must have occurred during Doug's, Emir's, and Pedro's prior behavioural engagement with their uncle, father, and grandfather (respectively) prior to the camp. That is, they had to perform intellectual reflection in order to transfer skills from the topics of furniture, toy-trains, and birdcages (respectively). The anticipated connection with perceived controllability is more preliminary in nature. We did note that the campers with more self-efficacy for ability (i.e., Doug, Emir, and Pedro) more often sought assistance from near-peer counsellors and adult co-advisors. We conjecture that cognitive engagement acted as an intermediary, as presumably the campers reflected before asking for specific tools or materials (e.g., asked specifically for more wire, rather than general requests for assistance). We hope that the conjectures prove useful to other educational designers in different contexts, in ways that provide 'needed links between theory and method' (Sandoval, 2014, p. 25) and 'simultaneously evaluate an intervention and test a theory' (p. 32).

Limitations and Future Directions

We note that our findings are immediately applicable only to the local context, though we do hope we have created an *existence proof of an educational model* (Bielaczyc, 2013) with design considerations that could be transferrable to additional contexts. The transferability of our model is supported by the finer-grained data and more diverse participants, relative to most previous studies on self-efficacy and student engagement (Schunk & Mullen, 2012). Further, our disaggregation of individual and social engagement (i.e., from a three- or four-part model to a six-part model) shows promise for addressing a variety of individualistic and collectivist approaches to knowledge and learning (Christenson et al., 2012; Fredricks, Wang, et al., 2016).

As noted in the Methods section, we had 22 campers complete questionnaires on all of Days 1-4, of the 29 campers who completed at least two questionnaires, amidst 33 total campers. The relatively low response rates (83% overall, and 57% on Day 5) do limit the quantitative analyses. We sought to address this deficiency by conducting a repeated-measures ANOVA for a complete data subset (22 campers on Days 1-4) and a multilevel modelling approach that included imputation of missing data (29 campers on Days 1-5; Raudenbush & Bryk, 2002). Nonetheless, some nuance has been lost from quantitative data. This loss is partially offset by the robustness of the qualitative data, which help us converge towards deeper understandings of campers' lived experiences during and before the invention camp (Creswell & Plano Clark, 2018).

We have already built on our findings and conjectures in subsequent camps. In planning for the 2022 camp, we will continue to explore the connections discussed in this paper. In general, we intend to keep addressing some of the concerns raised by Schunk and colleagues (Schunk & DiBenedetto, 2016; Schunk & Mullen, 2012), including grain-size of data sources, diversity of participants, and inclusion of out-of-school-time programming.

Concluding Remarks

Student engagement remains a central concept for educational practitioners, researchers, evaluators, and designers across the world, extending from its origins in school-dropout studies, reliance on pre/post research designs, and predominantly-Western contexts towards more asset-based, nuanced, and sociocultural approaches (Christenson et al., 2012; Fredricks, Wang, et al., 2016; Schunk & Mullen, 2012). Engagement shows promise for connecting scientists of all ages (including students) and the general public (McKinnon & Vos, 2015). The current study provides both detailed evidence and design conjectures to advance understanding of the individual|social dialectic of student engagement, in ways that promote the development of youths' self-efficacy (Fredricks, Wang, et al., 2016; Olitsky & Milne, 2012; Sandoval, 2014; Schunk & Mullen, 2012). We hope that this study serves as an existence proof that is also a useful educational model (Bielaczyc, 2013), so that youth may use invention education and similar design-oriented methods to more equitably participate in the natural sciences amidst inter- and trans-disciplinary projects.

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Section IV (Paper #3), "Inventors Emerging In- and Out-of-School: Five Years of Adolescent Student Engagement in Classes and Camps"

1. Introduction

User- and activity-centered design activities, such as inventing, are ways to create meaningful learning experiences with youth, including technological innovation in science, technology, engineering, arts, and mathematics (STEAM; Invention Education Research Group, 2019; National Science and Technology Council, 2018). Such transdisciplinary, project-based learning is especially powerful when done across in-school-time and out-of-school-time contexts, particularly through partnerships of local, regional, and national organizations (Bevan et al., 2010; Njoo et al., 2018). It can be challenging to research and evaluate across contexts for student outcomes related to interest, identity, academic performance, and career attainment; however, engagement has shown potential in linking a variety of topics of interest to communities, policy makers, and practitioners (J. Bell, Crowley, et al., 2019; Christenson et al., 2012; Sneider & Allen, 2019).

We share understandings from our five-plus years in a community-practice-research partnership based in "Mills City"[3], a semi-urban city near Boston, Massachusetts. For in-school-time classes and out-of-school-time camps and clubs, we co-designed and co-created learning environments with middle-school youth, who engaged in user- and activity-centered design through invention projects. The classes and camps in particular have included youth of one or more populations historically

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[3] All K-12 city, district, educator, school, and youth names are pseudonyms.

marginalized from participation in STEAM. We hope that in sharing our understandings we will join a broader conversation about co-designing formal, informal, and hybrid environments – as well as connections and transitions between these models – an especially important conversation during school phase-in's and phase-out's amidst the COVID-19 pandemic (Allen et al., 2020). Though engagement may manifest in different ways over time and space, it remains a key predictor and outcome of academic, career, civic, and personal importance.

2. Communities: "Mills City" & beyond

Mills City is situated on the traditional lands of the Massachusett and Pawtucket peoples. These first inhabitants were displaced by colonists first for farmland, then for mills during the US Industrial Revolution, and most recently offices for businesses and housing for both immigrant and gentrifying populations. The present-day population is diverse in terms of race/ethnicity, gender, cultural and linguistic background, national origin, and socioeconomic status. Thus, Mills City in many ways is a microcosm of past and current life in what is currently called the US. (See Table 4.1 for rounded racial/ethnic data.)

Table 4.1

Rounded Racial/Ethnic Data for the Two Middle Schools in Mills City

	Af.-Am.	As.	H	MR, NH	NA	NH, PI	W
CMS	10%	5%	60%	<5%	<5%	<5%	30%
NMS	10%	5%	25%	5%	<5%	<5%	55%

Notes. Due to rounding, school totals might not be 100%. CMS = Central Middle School; NMS = Northeast Middle School; Af.-Am. = African-American / Black; As. = Asian / Asian-American; H = Hispanic(/Latinx); MR, NH = Multi-Race Non-Hispanic; NA = Native American; NH, PI = Native Hawaiian or Pacific Islander; W = White.

Though our work centers on middle-school youth, it includes higher schoolers as "counselors"; practitioners as "teachers", "co-advisors", or "co-facilitators" (of classes, clubs, and camps, respectively); curriculum designers for creation, adaptation, and modification of curricula; university-based researchers as "participant-observers" who work at the intersection of research and practice; school-district leaders who ensure alignment with Mills City Public Schools' district improvement plan; and local workers and residents who participate in all aspects of programming. This strong foundation in local communities connects with broader cultural and professional communities, as will de detailed in following section about designed learning environments.

3. Designed Learning Environments: Five-plus Years of Curriculum-Revising, Camps, Classes, and Clubs

Our research-practice-community partnership began in Autumn 2016, when we revised the *Shoe Soles* curriculum for a February 2017 vacation camp, wherein campers invented outsoles for shoes. In Autumn 2017 we collaboratively designed our first learning experiences for a class setting, adapting the *Chill Out* curriculum for inventing an insulating device the size of a shoebox. Since then, we have facilitated two more camps and two more classroom interventions, which we summarize in Table 4.2 and Figure 4.1.

The main goals of the Lemelson-MIT JV InvenTeams Program are to "cultivate new ways of thinking and develop technical skills", especially for grades 7-10 youth "with limited access to hands-on STEM enrichment activities" (Massachusetts Institute of Technology [MIT], 2016, p. P4). Each of the nine curriculum units has a main project, as

Table 4.2

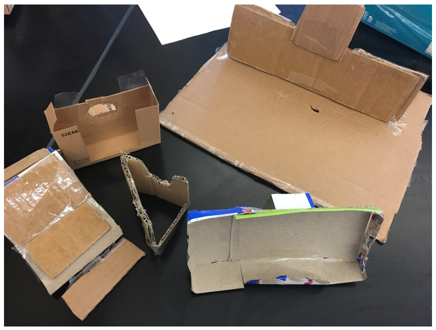
Summary of Designed Learning Experiences

Setting	Curriculum	Invention product(s)	Disciplinary Core Ideas (DCIs)*	Selected Performance Expectations (PEs)	Interdisciplinary connections*	Meaningful beneficiaries
February 2017 camp	*Shoe Soles*	shoe outsoles + free-choice invention	LS1.A: Structure and Function PS1.A: Structure and Properties of Matter PS1.B: Chemical Reactions	MS-LS1-4. Use argument ... to support an explanation for how characteristic animal behaviors and specialized plant structures affect the probability of successful reproduction….	Common Core: RST.6-8.1, RI.6.8, WHST.6-8.1	basketball players; dancers; runners
February 2018 camp	*Noise Makers*	electronic musical instruments + free-choice invention	PS2.B: Types of Interactions	MS-PS2-3. Ask questions about data to determine the factors that affect the strength of electrical and magnetic forces.	Common Core: RST.6-8.1 MP.2	musicians
February 2019 camp	*U Control*	electronic door + free-choice invention				pets (birds, dogs, snakes); younger siblings
Autumn 2017 class Autumn 2018 class Autumn 2019 class	*Chill Out*	shoebox-size insulating device	PS3.A: Definitions of Energy PS3.B: Conservation of Energy and Energy Transfer	MS-PS3-3. Apply scientific principles to design, construct, and test a device that either minimizes or maximizes thermal energy transfer.	Common Core: RST.6-8.3, WHST.6-8.7	survivors of disasters and/or power outages, especially with temperature-sensitive meds in rural areas

*Note. All curricula included the Disciplinary Core Idea of "Developing Possible Solutions" (ETS1.B). Also, all curricula promoted *trans*disciplinary learning through inventing, entrepreneurship, and project-based learning.

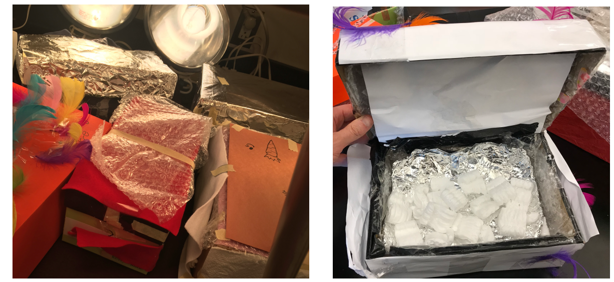
Figure 4.1

Representative Photos of Designed Learning Environments



(A) Rapid prototyping I: Stands for tablets and/or mobile phones

(B) Rapid prototyping II: "Problem Strips" for common situations



(C) *Chill Out* for small, insulating devices

(D) *Shoe Soles* for outsoles of shoes (models pre-molding and -casting)

(E) *Noise Makers* for electronic musical instruments

(F) *U Control* for electronic doors.

Note. Required safety equipment included safety glasses, latex-free gloves, and close-toed shoes.

well as a follow-up activity for free-choice inventing. Within each unit, all sessions conclude with a self-assessment, in which youth reflect on their development of self-efficacy in science, user- and activity-centered design/engineering, and inventing. Overall, the program considers (technological) inventing to be the creation of a "useful and unique" contrivance, which can potentially be patented and produced in large quantities through entrepreneurship.

Each intervention included the Types of Team Members framework, developed by the Lemelson-MIT JV InvenTeams program. Youth self-identify with four roles: *Doodler* (of sketches, diagrams, etc.), *Organizer* (of materials, tasks, and persons); *Talker* (within and between teams, as well as with community members); and *Tinkerer* (with materials, supplies, prototypes, and final products). We found that these roles had varying degrees of fluidity, as will be detailed in the subsection, "Key Challenges".

In policy, the district improvement plan includes a specific priority for science, technology, engineering, and math (STEM) at the middle school level, as well as more general priorities of additional learning-time that can be partially realized through partnerships with external organizations. In practice, the grades 6-8 STEM camps and clubs provide enrichment and extension, allowing students to go both broader and deeper into topics of interest to them.

The research team from Boston College prioritizes student (re-)engagement in STEM, particularly for youth from marginalized populations. The researchers include students spanning grades 13-20, a lab manager, a senior research scientist (post-doctoral), and a university Professor, all of whom take a social justice orientation towards fostering youths' confidence, interests, and identities, while developing transferrable skills of communication, critical thinking, and problem solving.

In describing the individual interventions, we proceed from out-of-school-time (OST) to in-school-time (IST), keeping chronological order in each. This sequence reflects the order of our programming, as well as invention education's expansion from a more OST-oriented field to a more balanced OST-IST hybrid (Invention Education Research Group, 2019).

3.1 *Shoe Soles* for Outsoles of Shoes (February Vacation Week, 2017)

The first camp was February 20-24, 2017, at Central Middle School in Mills City. Campers worked in teams of between two-four members to make shoe sole prototypes in a process that involved researching, drawing, sculpting, molding, and casting. The camp culminated in a public Showcase of student work. (See Figure 4.2 for photos of the process.)

We adapted a 14-hour curriculum for the 26 hours of camp activity-time, allowing additional time for free-choice inventing and for videoconferences with invention professionals. (An agenda for the camp and a list of supplies can be found in the Supplemental Materials.) Before the camp, we planned for 7.5 hours of training, but could only conduct 2.5 hours due to inclement weather. A total of 27 campers attended at least one day of camp, with an average of 23 campers per day (4.4 days per camper). Eleven campers were from races/ethnicities underrepresented in STEM, and nine self-identified as female (plus 18 as male).

Figure 4.2

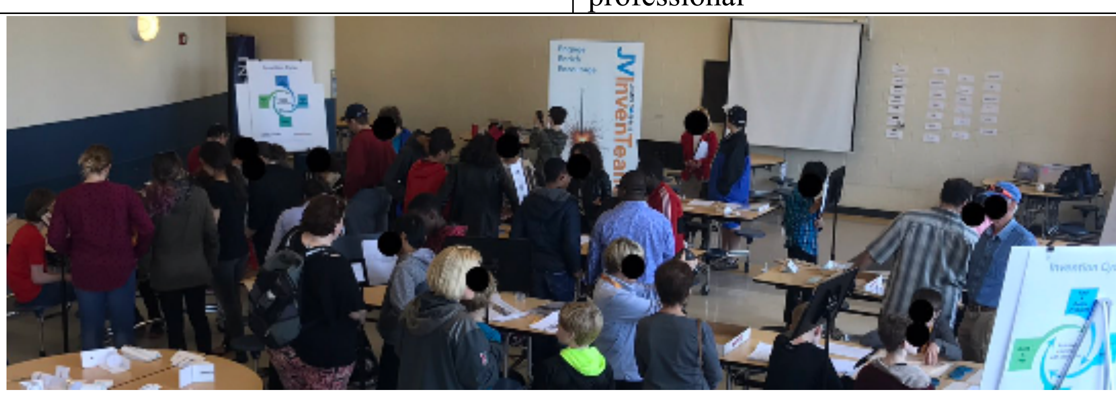
Making Shoe Soles, Videoconferencing with Professionals, & Showcasing in Community

(A) Clay model [top] & plastic mold [bottom]

(B) Plastic cast; purple chosen (final product)

(C) Youth safely creating casts from molds

(D) Conference with invention professional



(E) Community showcase, attended by administrators, community members, families, and friends

The first day was devoted to general invention activities, such as rapid prototyping (see Figure 4.1A and 4.1B). On the morning of the second day, we introduced biomimicry (design inspired by organisms) and fundamentals of shoe-sole design, including an afternoon sculpting clay models of shoe soles. Campers created rubber molds on the morning of day three, then spent the afternoon learning about specific inventors and the role of empathy in invention. On the fourth day youth poured casts into the rubber molds, then had time to plan their own inventions. Finally, on the fifth day the campers tested their prototypes and presented them in a public Showcase. Throughout the week there were generally three or more adult facilitators and two or more university participant-observers present at any given time.

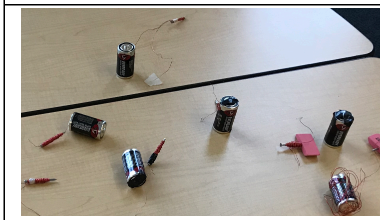
3.2 *Noise Makers* for Electronic Musical Instruments (February Vacation Week, 2018)

Our second camp was February 19-23, 2018, again at Central Middle School. Campers worked in teams of between three-four members to make electronic musical instruments, which included single electromagnets that converted mechanical vibration of strings into electrical signals (i.e., electrical "pickups"). However, not all campers chose to incorporate a pickup into their final design, while some campers made *double*-pickup designs. The camp once more culminated in a public Showcase of student work. (See Figure 4.3 for representative photos.)

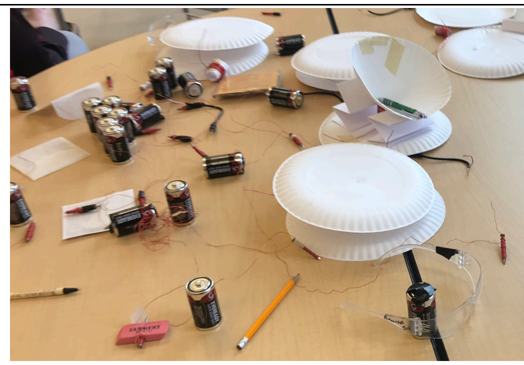
Same as 2017, we expanded the activities given the additional time-on-learning, relative to the original curriculum. Further, based on feedback from campers and co-facilitators ("students" and "teachers", respectively), we planned for more time to be

Figure 4.3

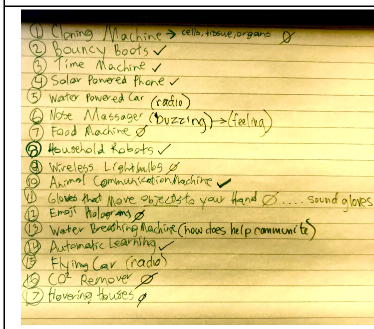
Creating Electric Musical Instruments, Invention Brainstorms, & Advertising Pamphlets



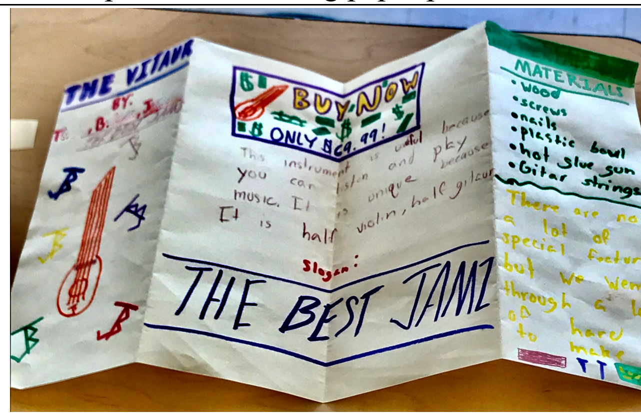
(A) Electromagnets from iron nails and copper wire, with erasers for spooling the wire



(B) electric speakers, including paper plates as membranes



(C) Team-based brainstorming for free-choice inventions



(D) Pamphlet advertising "The Vitaur" (a violin-guitar hybrid)

(E) Instrument made from extra pipes found in a hallway, played with cardboard mallets

(F) Foot-drum made from tape and scrap-wood

(G) Guitar with one pickup (see Figure 4.1E for guitar with two pickups) devoted to free-choice inventing (about 4.5 hours in 2018, compared to about 3 hours in 2017). A total of 32 campers attended at least one day of camp, with an average of 26.2 campers per day (4.09 days per camper). Of the 30 campers who opted-in to the research component of the camp, 16 were from races/ethnicities underrepresented in STEM (with three declining to self-identify), 14 self-identified as female (and 16 as male), and nine completed their applications in Haitian Creole or Spanish (21 in English).

As in 2017, the first day was devoted to general invention activities, such as rapid prototyping (see Figure 4.1A and 4.1B), along with taking apart headphones and building electromagnets (see Figure 4.3A). On the second day, we built speakers (Figure 4.3B), started making musical instruments, and did a youth-led activity on empathy. Day three included construction of electrical pickups, roughly two hours of free-choice inventing, and a videoconference with a drummer-and-inventor. The fourth day was mostly for revision of instrument prototypes and of plans for free-choice inventions, as well as a videoconference with a high-school senior who had extensive music and invention experience. Finally, on the fifth day the campers completed their prototypes, plans, and some informational pamphlets or slideshows, which they presented in a public Showcase. Throughout the week there were again usually three or more adult facilitators and two or more participant-observers present at any given time.

3.3 *U Control* for Electronic Doors (February Vacation Week, 2019)

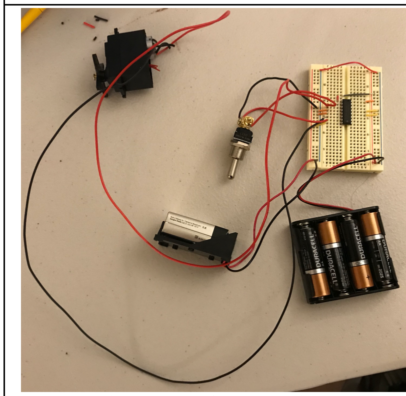
Our third camp was February 18-22, 2019, once more at Central Middle School. Campers worked in teams of between three-four members to make electronic doors, using electronic prototyping boards (a.k.a. “breadboards”; Figure 4.4A) that interfaced with a three-position switch and a servo motor to open and close foamboard doors (Figure 4.4B). The curriculum called for a 61 cm x 46 cm frame with a 30 cm x 30 cm opening (24” x 18” frame and 12” x 12” opening; Figure 4.4D). However, some campers elected for larger or smaller designs. For example, Figure 4.1F shows a design for a small pet, and Figure 4.4C is for a younger sibling. The camp culminated in a public Showcase.

Due to a weather delay, we had two fewer hours of activities (24, compared to 26 in previous years). A total of 31 campers attended at least one day, with an average of 27.8 campers per day (4.48 days per camper). Of the 31 campers who opted-in to the research component of the camp, 12 were from races/ethnicities underrepresented in STEM (with one declining to self-identify), six self-identified as female (and 25 as male), and seven were emergent multilingual campers. We were concerned by the disparity of female and male campers, a phenomenon we partially attribute to low interest in the topic, which was likely exacerbated by culturally and socially gendered behavior norms, as will be elaborated in the “Successes & Challenges” section.

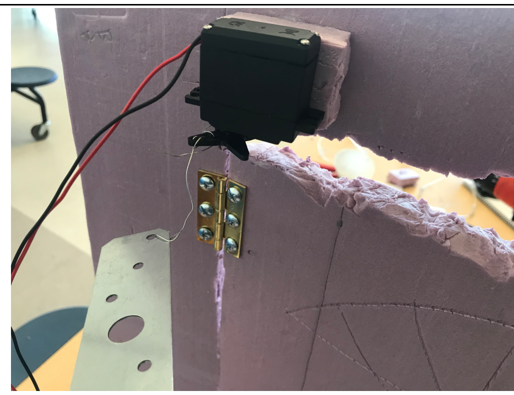
The first day’s session included abbreviated versions of rapid prototyping, as well as some activities related to simple machines. Day two focused on cutting the door’s frame and the door itself, then using an electrical circuit to control a servo motor. The third day was for connecting the electrical and mechanical parts, then about two hours for free-choice inventing. Day four had another 1.5 hours of free-choice inventing, some time for revising designs of electric doors, and two videoconferences (one with an intellectual-property attorney, and the other with an Assistant Professor of Art). The final day included time to complete all prototypes, plans, and pamphlets – the latter of which

Figure 4.4

Creating Electric Doors, using Principles of Current Electricity & Simple Machines

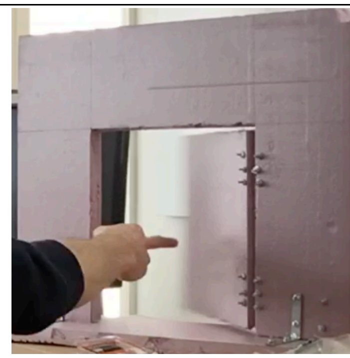


(A) Using an electronic prototyping board ("breadboard") to include a three-position switch for controlling the door (forward-off-reverse)

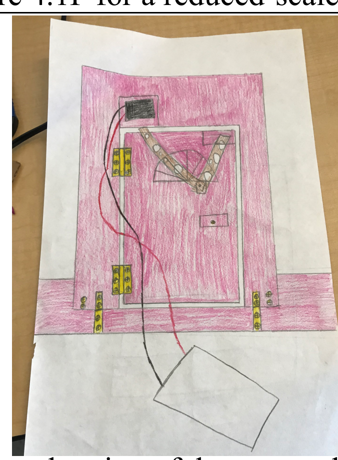


(B) Close-up photo of servo motor when connected to metal arm, for increasing torque on the door during opening

(C) Scale of door roughly doubled, relative to the student curriculum guide



(D) Scale of door when replicating the instructions in the student curriculum guide (see Figure 4.1F for a reduced-scale door)



(E) Camper-drawing of door assembly (breadboard not yet detailed) included some specific guidance around procedure writing – before the camp's conclusion with a community Showcase.

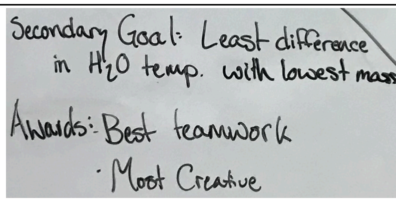
3.4 *Chill Out* for Shoebox-size Insulating Devices (Autumn Semester, 2017-2019)

Our in-school-time partnership is described elsewhere, with a detailed scope-and-sequence, student work artifacts, alignment with the Next Generation Science Standards, interdisciplinary connections, safety concerns, classroom management tips, and material costs (see Supplemental Materials for costs from all projects; Zhang et al., 2021). The student and teacher guides are available online, free of charge. In brief, the curriculum involves students designing and building shoebox-size insulating devices, using principles of heat transfer (conduction, convection, and radiation), biomimicry (e.g., of penguins and seals), and thermoelectric effects (including a Peltier tile for converting electrical energy to thermal energy; see Figure 4.5 for representative photos). Along curriculum-embedded connections like urban heat islands, students identified needs for daily lunchboxes, longer-term food storage, and medical transport, especially in situations where electrical grid access is scarce (e.g., in rural areas and/or due to natural disasters). For the purposes of this article, we will frame the in-school-time classes in respect to similarities and differences with the out-of-school-time camps.

We partnered with both middle schools in Mills City, Northwest Middle School (NMS) and Central Middle School (CMS). The racial/ethnic demographics of the two middle schools are shown in Table 4.1. CMS has tended to have more multilingual students and families, so the members of the research team with specialties in language-

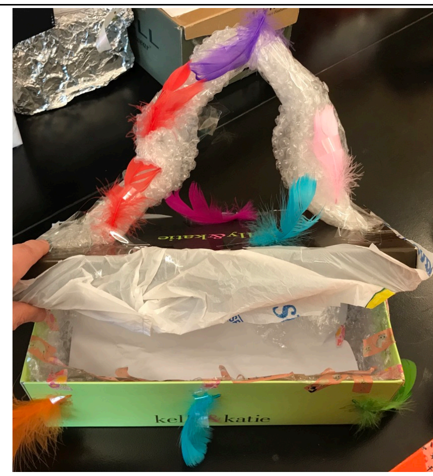
Figure 4.5

Creating Shoebox-size Insulating Devices, Conducting a Contest, & Sharing via Posters

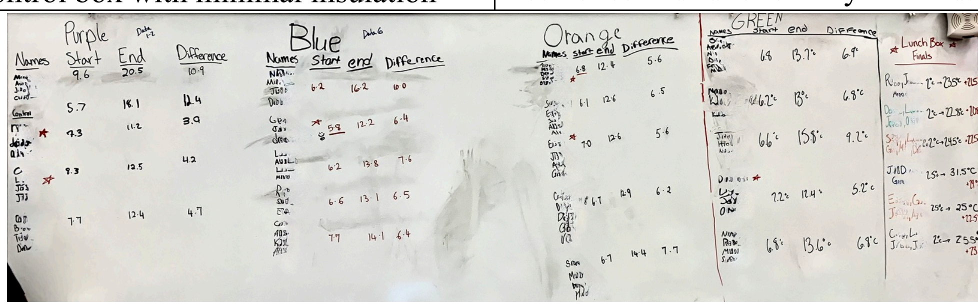


(A) In addition to the primary goal of minimizing temperature, there were prizes for efficiency, collaboration, and creativity.

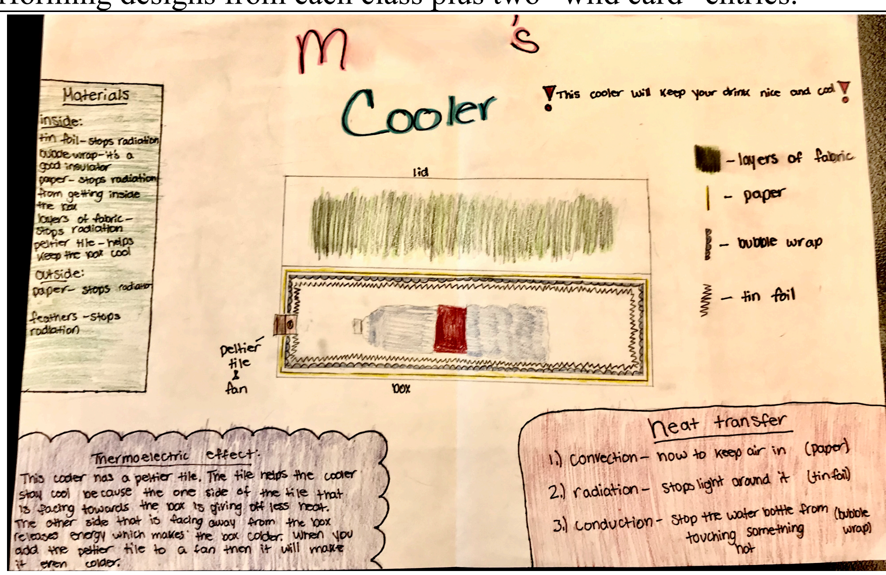
(B) Control box with minimal insulation



(C) Teams created boxes with both aesthetics and functionality in mind.



(D) Each of four classes had its own "contest", followed by a cluster-wide competition of the top performing designs from each class plus two "wild card" entries.



(E) Youth created posters for science, engineering, and invention concepts.

learning worked more closely with CMS. On the other hand, research specialists in science education tended to focus on NMS.

The racial/ethnic and linguistic (alternatively, raciolinguistic) dynamics manifested differently across the two schools. For example, at CMS teachers emphasized the value of literacy-based activities such as procedure- and patent-writing. At NMS, teachers noticed both US- and internationally-born students making connections with their ancestors from up to several generations ago (e.g., when talking about how their "home cultures" keep things hot or cold). In sum, the curriculum showed flexibility in adapting to two very different school and community contexts within the same city, as implemented by classroom teachers with researcher-participant support.

4. Successes & Challenges

Across the three in-school-time interventions of one invention project and the three out-of-school interventions of different invention projects, some patterns have emerged for student engagement, along with processes of developing self-efficacy for science, design, and inventing. Though the long-term nature of our partnership has enabled us to change some initial challenges into eventual successes, other challenges still remain.

4.1 Key Successes

Overall, the interventions have been successful at engaging students in affective, behavioral, cognitive, and social ways (Zhang et al., 2021). One major finding is that social engagement seems to counteract individually-based anxiety, especially for in-school-time interventions. For example, seventh-grader Daniela stated that "…there was other people working with me that could help me, and it wasn't really something to get anxious about." Another key finding is the increased engagement during out-of-school-time implementations, relative to in-school-time implementations. This difference is clear in quantitative data, such as the item, "I pay more attention in vacation camp than I do in school science", for which responses averaged 5.5/7 for the entire camp and 5.9/7 for Days 2-5, the more hands-on and project-focused days. Those averages indicate a slight to moderate agreement that students paid more attention in vacation camp. Though we recognize that in-school-time and out-of-school-time environments come with different affordances and limitations, we agree with eighth-grade camper Pedro that in-school-time environments could benefit from "more freedom" without teachers checking-in "every five seconds".

In terms of self-efficacy, we found evidence that students developed through their conceptions of ability, as well as through their management of anxiety. Unsurprisingly, the most pronounced developments are the most closely connected to a given curriculum unit (e.g., "I can demonstrate heat transfer", "I can apply my understanding of electromagnetism to build an electric door", etc.). On the other hand, we have seen little development related to more abstract or domain-general skills (e.g., "I can work in MANY different ways on *my own* invention project" and "I can work in MANY different ways as part of an invention *team*", etc.). Though the high turnover rate for our middle-school camps has thus far hampered efforts to examine possible long-term development of the more abstract skills, we are optimistic in part due to findings about self-efficacy and identity development on high-school invention teams (Invention Education Research Group, 2019). Perhaps most importantly, we are encouraged that differences

in self-efficacy development have not widened any gaps with respect to gender or race/ethnicity, and occasionally have narrowed such gaps.

Over time we have made a revised curriculum, increasing accessibility through differentiating for (dis)abilities, interests, modalities, and linguistic registers. In expanding the *Chill Out* problem framing from a “lunchbox” to an “insulating device”, we created space for students to generate culturally relevant problems like medicine transportation and food preservation. For *Noise Makers*, we allowed two or zero electronic pickups, instead of mandating precisely one. During *U Control*, we supported designs that doubled or halved the expected size, including some that had doors-*within*-doors. In addition to those design choices to leverage interest, we did a labor-intensive conversion of the *Chill Out* curriculum from PDF to Google Doc format, enabling students to use dictionary, translation, highlighting, and screen-reader tools. For students sensitive to loud noises, we gave extra space and did woodworking per their instructions. Some youth with diagnosed disabilities for processing or executive function required more frequent check-ins. Finally, in offering summative assessments like posters, presentations, pamphlets, and video advertisements, we encouraged the use of colloquial language that nonetheless addressed canonical science.

4.2 Key Challenges

Despite quantitative evidence that gender was not a statistically significant factor for engagement and self-efficacy, some qualitative findings suggest that more work is needed to ensure equitable participation for students of all genders. For example, during the *U Control* camp for electric doors, a mixed-gender group had two boys doing most of the tinkering and two girls doing most of the doodling. In post-interviews, the girls expressed a desire for more intra-team talking, which could have been facilitated by high-school counselors and adult advisors. We have since adjusted our training sessions to include more pedagogical knowledge and pedagogical content knowledge, whereas previous trainings overemphasized content knowledge.

One minor challenge remains survey response rates, especially during out-of-school-time. In hindsight, we may have been overly cautious in our efforts to avoid taking too much space for student questionnaires, especially when trying to preserve a less "school-like" environment during out-of-school-time. Distributing surveys earlier in camp days should reduce the number of missed responses due to students leaving early or hastily. For in-school-time, more streamlined formats like Google Forms could yield the same information as the more complicated survey software we have used in the past, whose advanced features are not necessary for these interventions.

Finally, we still have work to do to support students in considering inventing as a career option. In pre-/post- measures from various interventions, career intentionality towards inventing has either remained stagnant or decreased. Though in part we can attribute this to more realistic conceptions of inventing (e.g., disrupting the myth of "lone wolf" inventors), we could do a better job of showing diverse approaches to inventing. One teacher in particular has taken extra time and energy to ensure that examples include amateur and/or adolescent inventors, an investment that she reports has resulted in increased student engagement during some of the more reading-, video-, and writing-intensive activities.

5. Design Implications & Future Plans

5.1 Implications for Educational Design

Our experiences suggest that educational designers – whether they work as curriculum specialists, classroom teachers, camp or club facilitators, or other roles – could benefit from thinking with a six-dimensional framework for student engagement. Namely, we found that affective, behavioral, and cognitive engagement are qualitatively different when approached individually or socially. For specific categories, we recommend individual-affective, individual-behavioral, individual-cognitive, social-affective, social-behavioral, and social-cognitive dimensions. This is not to say that categories should be approached exclusively in isolation; rather, educational design should consider how various dimensions support each other (Christenson et al., 2012). Recalling an earlier example, the mixed-gender group members from *U Control* were engaged or disengaged in individual-behavioral and individual-affective senses (i.e., boys consistently excited with tinkering and girls eventually bored with doodling), yet they were *not* engaged in social-behavioral or social-affective ways (i.e., group members neither talking much with each other nor substantially emotionally supporting each other). We found that this example and more suggest that invention education – with its personal relevance and team-based approach – is a particularly fertile field for exploring the six-dimensional model of student engagement.

Though it might appear that the out-of-school-time implementations prioritized engagement and interest at the expense of conceptual understanding and canonical practices (and vice versa for in-school-time learning), we agree with prior work showing that each setting can and does promote both affective and cognitive outcomes (Bevan et al., 2010; Sneider & Allen, 2019). For example, we found that in-school-time learning could foster joy while mitigating anxiety, and that out-of-school-time learning can promote deeper cognitive engagement with topics previously explored through casual hobbies (e.g., deepening concepts of electricity or simple machines, that were initially approached with toy trains or furniture-making).

In terms of measurement, we recommend that student self-assessments are expanded both in response scale and in gradations of challenge. For example, we found that seven-point scales worked better than five-point scales, which in turn worked better than our initial three-point scales. Also, we noticed that adding modifiers like "very" and "many" allowed us to see finer-grained changes in students developing self-efficacy (e.g., "I can work *very* well…", "I can think of *many* uses…"). Further, these self-assessments should be given well before the end of a session, as we have found that many students run out of time or leave a little early, especially during camps. These self-assessments can aid not only in youths' personal reflection and meta-cognition, but also as formative assessments for educational design and implementation (J. Bell, Crowley, et al., 2019; Sneider & Allen, 2019).

Finally, a concern that we anticipated would be important yet we nonetheless underestimated, is the importance of topics being high-interest to youth. Though it can be time-intensive to update existing curricula for more recency and relevance, in our experience that time has been worthwhile. One way to share the workload, which also adds a diversity of experience, is to include near-peer youth in the planning process (e.g., high-school youth as co-designers of interventions for middle-school youth). For us, it took a year to establish strong connections between adults and high-schoolers in terms of co-design, which ultimately proved to be a beneficial investment.

5.2 Future Plans

Moving forward, we plan to design for three-student groups as much as supplies will allow, despite the four-part Types of Team Members framework. We believe that such a decision will allow for both individual responsibility *and* collective flexibility. Namely, each teammate will have a primary role alongside a share of the one undesignated role. We hope that this design consideration will encourage a firmness yet fluidity in task-sharing, as we saw in varying degrees during the *U Control* implementation in particular.

Another change we will make is diversifying the awards or recognition for in-school-time interventions. While we acknowledge the general scientific and NGSS-specific importance of an insulating device's *effectiveness* (i.e., minimizing temperature change), we also seek to encourage sustainability by awarding prizes or other attention for *efficiency* (i.e., minimal temperature change AND minimal and/or sustainable materials use). Further recognition could expand to disciplines related to technological inventing adjacent to the "STEM" umbrella, such as precision of patent writing (language arts), attention to sociocultural concerns of users/clients/benefactors (social studies), and aesthetic appeal (visual arts).

Finally, we plan to extend our work into developing fields like sustainable chemistry and physical computing. Already we have piloted units on earth-friendly bioplastics (*Green Chemistry*) and microcontroller-connected toys (*Toy Design*, with BBC micro:bit), developing or maintaining partnerships with local businesses. Revisions of the pilot curricula are ready for future camps, and will replace units that stimulated less interest in past years.

6. Conclusion

Supported by strong connections amongst community members, district-level policy-makers, practitioners, researchers, and youth, our collaboration has resulted in *Shoe Soles* becoming part of the district-wide 7th grade curriculum; an annual oversubscription to the February camp; and several units in after-school clubs that we omit here for conciseness. As the in-school-time and out-of-school-time implementations continue to inform each other, the research-practice-community partnership seems poised to continue fostering student engagement in Mills City, and hopefully beyond.

Supplemental Materials

Supplemental Materials are available here:

https://drive.google.com/drive/u/1/folders/1Ngf7nHrf2h_gGOa-s7LD6NevQXYDLo9Q

Costs of Materials

Kits are available for purchase, though actual costs might be roughly half of kit prices, if a learning environment already has some durable goods (e.g., safety goggles, measuring cups or large cylinders/beakers, a way to boil water, thermometers, etc.).

For example, the full prices ranged from $450-$950 for a 20-student kit. However, for a $450 kit, we only needed $195 of durable supplies per *teacher*, plus $90 of consumable supplies per *class*. In other words, rather than spending $1800-$2250 for 80-100 students, our actual costs were around $555-$645 for 80-100 students (Zhang et al., 2021).

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Section V: Discussion of the Three-Paper Set

Overview

This three-paper set reports on student engagement in science and user-centered engineering, with connections to expression and changes of self-efficacy. The first two papers were based on case-oriented analyses (Miles et al., 2014), with the cases being an in-school-time project and an out-of-school-time camp. The third paper was based on variable-oriented analyses (Miles et al., 2014), with variables related to six dimensions of student engagement, 13 ways self-efficacy affects development, and 18 design considerations, along with pattern and axial codes thereof (Saldaña, 2009). This section first presents the most salient findings for practice and theory; it then outlines the dissertation's contributions to the fields of student engagement and self-efficacy, as situated in science and user-centered engineering; and it ends with future directions for practice, research, and policy.

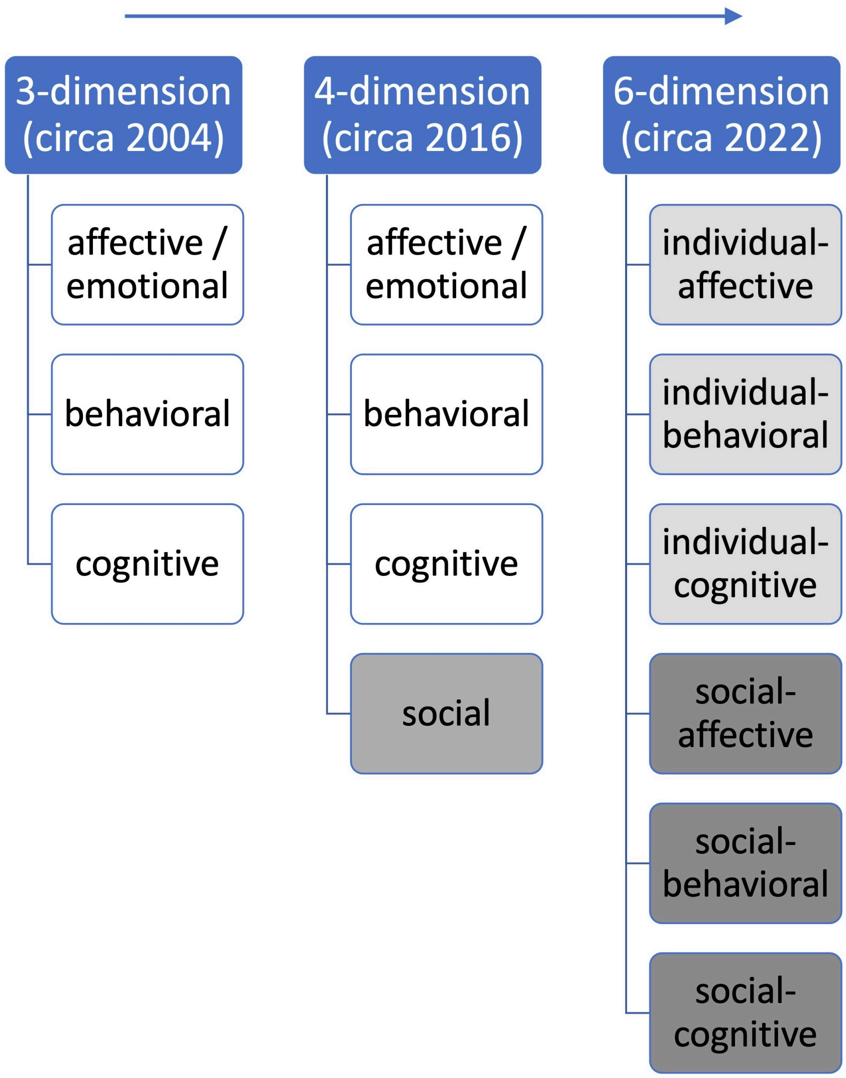
Integrated Findings

Findings for Student Engagement

The three papers support evolution to a six-dimensional model of student engagement, as an extension of traditional three- and four-dimensional models (Fredricks, Wang, et al., 2016). This evolution is represented in Figure 5.1. In support of this conceptual evolution, the papers find empirical differences between individual and social manifestations of engagement. See Table 5.1 for representative examples.

Figure 5.1

Progression of Dimensional Models for Student Engagement, 2004-2022



The evidence is mostly qualitative in nature. An overall lack of statistically significant quantitative support in this regard might be due to the brevity of the interventions (Invention Education Research Group, 2019) and the survey design, namely the response scale and the gradations of challenge (i.e., the breadth of the outcome space and the extremity of the prompts' phrasings; Bandura, 2006).

Table 5.1

Qualitative Differences for Individual and Social Levels of Engagement

	individual	social
affective / emotional	Excitement to make an electronic door for his pet birds	Excitement for successes of teammates (e.g., wiring)
behavioral	Using screws and brackets to fasten door frame to base board (alone)	Working with teammates to have one person hold parts while the other person fastens the parts
cognitive	Awareness of which tasks needed to be done (*list* of requirements)	Awareness of how the tasks were shared amongst teammates (*distribution* of requirements)

Note. All examples are for “Pedro” from Team #2 in Paper #2.

Findings for Self-Efficacy

Across the three papers, self-efficacy was consistently affected by *social circumstances* through *enactive* and *emotive* sources (Bandura, 1977), often shaping development through cognitive processes related to *ability* (Bandura, 1993). Returning to Team 2, interactions were affected by social considerations like friendships both within and across invention teams; by previous inventing experiences with friends and family; and by the perceived social relevance of the project. The enactive sources include prior successes with toy trains and wooden furniture, current successes with wiring and assembly, and future possibilities of even more relevant projects. Some examples of emotive sources include love for one’s own pets, excitement at using power tools, and pride in a functional final product. All of those sources affected campers' conceptions of their own ability to complete various tasks, such as Emir's confidence with wiring and Pedro's confidence with assembly.

Together, the findings extend self-efficacy in both theory and practice, from its more clinical and individual beginnings towards more naturalistic and social applications (Bandura, 1977; Schunk & DiBenedetto, 2016). The three papers provide insight into self-efficacy in both in-school-time and out-of-school-time settings, as well as how possibilities for how self-efficacy might manifest in more structured out-of-school-time settings or more open-ended in-school-time settings.

Findings for Educational Design

For both design and analysis, this study used the 18 design considerations of the Social Infrastructure Framework (SIF; Bielaczyc, 2006). Across the three papers, two considerations emerged as most salient: *How a student's social identity is understood* (from the *Cultural beliefs* dimension) and *The planned learning activities* (from the *Practices* dimension). The interplay between these two considerations radiates implications for both student engagement and self-efficacy. For example, positioning youth in identities as Tinkerers, Talkers, Organizers, and Doodlers (Massachusetts Institute of Technology [MIT], 2016) implies which activities "count" as behavioral engagement (e.g., assembling the door or insulating device; presenting the final product to a community or class; coordinating tasks, tools, and materials; and making preliminary sketches or final diagrams, respectively). This behavioral engagement affects students' self-efficacy, through ideas of what “counts” as successful enactment, desirable emotions, or useful ability.

Through pattern coding (Saldaña, 2009) of which groups seemed more flexible and equitable across the four prescribed roles, two key design elements emerged. First, it was revealed that despite (or perhaps because of) the *four*-role framework, teams of *three* showed more desirable dynamics in terms of individual participation and group collaboration. Second, it was shown that the curriculum needed to ensure a relatively equal balance of the four roles, lest one or more roles get marginalized (especially per gendered and/or racialized stereotypes). These design elements can inform educators implementing the projects, as well as curriculum developers revising the projects.

Contributions to the Fields of Student Engagement, Self-Efficacy, and Educational Design

Contributions for Student Engagement

This three-paper set contributes to expansive notions of student engagement, within the debate in the field about three-, four-, and six-dimensional models. The evidence for a six-dimensional model includes a social *level* of engagement in a dialectic with an individual *level* of engagement, rather than making an omnibus “social engagement” its own distinct *dimension*. This distinction will guide practitioners, researchers, and evaluators in maintaining a holistic stance towards student engagement, avoiding both hyper-individualistic and hyper-collectivist stances.

In considering student engagement *as* theory, the six-dimensional model is commensurate with theories of motivation, flow, and self-determination. Further, the six-dimensional model encourages dialogue with multiple worldviews, including pragmatic, cognitivist, post-positivist, social constructivist, transformative, and other philosophies (Creswell & Plano Clark, 2018). Metaphorically, it embraces head, heart-and-soul, and hand in both individual and collective ways, showing that the "elusive science" of educational research (Lagemann, 2000) can effectively be addressed interdisciplinarily through the learning sciences (Yoon & Hmelo-Silver, 2017).

Contributions for Self-Efficacy

This dissertation provides insight into the "dynamic nature" (p. 49) of self-efficacy, addressing a need for finer-grained data sourcing with more racially/ethnically, culturally and linguistically, and socioeconomically diverse participants in both in- and out-of-school settings (Schunk & DiBenedetto, 2016). Specifically, it moves beyond a pre-/post- design to include mid-surveys (one IST and three OST), video recordings, audio recordings, and ongoing field notes. It includes participants with affinity for Eastern and Global South cultures (e.g., East Asian, South Asian, Central American, Caribbean, and Sub-Saharan African), expanding previous work mostly conducted with Western and/or Global North populations. In sum, the research design allowed for shorter-term and more nuanced understandings of self-efficacy development, including minor successes and failures throughout two human-centered engineering projects, brief interactions between teammates, and translingual communication repertoires. This study builds on self-efficacy's foundations in primary adult-centered cognitive psychology and social psychology, as it contributes to the field's expansion into naturalistic educational settings with youth (Bandura, 1977; DiBenedetto & Schunk, 2018; Schunk & DiBenedetto, 2016).

Contributions for Educational Design

In a follow-up to the original paper on Social Infrastructure Framework (SIF; Bielaczyc, 2006), Bielaczyc (2013) described the importance of *implementation paths* that help educators "toward a more robust implementation of the desired model" (p. 264), for example, a project based on user-centered engineering or invention education. The current study suggests design considerations of importance for in-school-time *and* out-of-school-time implementations (IST and OST, respectively), as well as single implementations that could seek to maximize affordances and minimize constraints of IST and OST. Further, the design considerations could support ways to optimize synergy of dual implementations (i.e., when students are known to participate in both IST and OST implementations). For example, the role of curriculum developer could be expanded to include youth who participated in a previous implementation. Indeed, some of the most insightful feedback on the 2019 camp (Paper #2) came from high-school-age counselors, who had participated in previous implementations when they were middle-schoolers.

Future Empirical, Conceptual, and Policy Directions

In line with calls for more holistic design-based research (O'Neill, 2016), this section is divided into empirical, conceptual, and policy directions, in the hope that research-practice partnerships span boundaries of who is traditionally labeled as researchers, practitioners, community members, students, policymakers, and so on.

Future Empirical Directions

Empirical work could develop new measurement suites for student engagement, which would include six dimensions as described earlier. Building upon the well-established four-dimensional suite by Fredricks and colleagues (2016), items could be slightly adjusted, as shown in Table 5.2. Such work was originally planned for this dissertation, until the COVID-19 pandemic canceled the intended intervention.

Table 5.2

Adjusting Four-Dimensional Engagement Items for the Six-Dimensional Model

	Four-dimensional	Six-dimensional
affective / emotional	I enjoy learning new things.	individual: I enjoy learning new things *by myself*. social: I enjoy learning new things *with classmates.*
behavioral	I answer questions.	individual: I answer questions *by myself.* social: I answer questions *with classmates*.
cognitive	I think about different ways to solve a problem.	individual: I think about different ways to solve a problem *when working alone*. social: I think about different ways to solve a problem *when working in a group.*
social	I try to understand others [*sic*] peoples' ideas.	N/A (Social items are the lower items, in each pair above. The higher items are individual items.)

Note. Four-dimensional items are from Fredricks and colleagues (2016, p.12).

Perhaps aided by new subscales, empirical work could also deepen understandings of design considerations for invention education in-school-time, building on mostly out-of-school-time interventions thus far (Invention Education Research Group, 2019). Invention education shows promise for more interdisciplinary approaches to education, such as project-based learning, especially when integrating science, technology, engineering, arts, and mathematics (STEAM). In this case, “invention” is an abbreviation for *technological* invention; principles from this field could be applied to other forms of inventing, such as inventing new political systems (Committee for the Study of Invention, 2004).

A third empirical direction is the study of collaboration when the number of roles is intentionally greater than the number of teammates. Such an educational design would force at least one teammate to switch roles, and might promote all teammates switching roles. Though the current study included preliminary evidence to support this educational design choice, more work is needed to verify its affordances and constraints in similar and different educational environments.

Finally, the current study could be extended through a third-generation activity theory analysis, as based in Cultural Historical Activity Theory (CHAT; Engeström, 2001; Gutiérrez et al., 1999; O’Neill, 2016). In this case, curriculum developers, teachers/facilitators, and campers/students would each have their own activity systems, from which would emerge one meta-system. Such an approach would extend the study from the microsystem to the mesosystem level (Bronfenbrenner, 1993), and perhaps beyond.

Future Conceptual Directions

As mentioned in the Introduction, this study is informed by a metaparadigm of *dialectical pluralism*, wherein diverse worldviews are given *equal* value in a research project or other collaborative endeavor . However, as argued by Onwuegbuzie and Frels (2013), dialectical pluralism does not ensure *equitable* value for the voices of historically marginalized populations. That is, to redress past and ongoing power imbalances related to race/ethnicity, gender, socioeconomic status, national origin, and other identity markers (Cho et al., 2013; Crenshaw, 1989), an overemphasis on marginalized voices is needed (Onwuegbuzie & Frels, 2013). Thus, future conceptual work in *all* major fields of this dissertation should more explicitly attend to issues of power and privilege.

For student engagement, self-efficacy, and the Social Infrastructure Framework, a more critical stance would expand what is meant by "social" and "environmental". These terms currently tend to remain at the levels of small-groups and classrooms/camps/clubs (Bielaczyc, 2006; Christenson et al., 2012; Schunk & DiBenedetto, 2016). Future work should include school-wide, municipal, (nation-)state, cultural, and temporal influences (Bronfenbrenner, 1993). For example, a social-affective item for student engagement might be, "I feel a sense of welcome and belonging in science class". A self-efficacy item could be, "I believe I can overcome systemic and institutional barriers to my participation in science class." The Social Infrastructure Framework could problematize *the technology itself*, taking into account concerns of economic, environmental, and health justice related to high-tech manufacturing and marketing (Gunckel & Tolbert, 2018). In all three fields, protocols should call attention to stereotyped roles, especially as they vary across disciplines (Tytler & Osborne, 2012; Wieselmann et al., 2020).

Future Policy Directions

While policy is not a focus of this study, the evidence does moderately support changes at the local level and incrementally at the (nation-)state level. At the local level, schools, districts, and networks could approve invention education as an elective or capstone course, along with supporting invention units within existing courses. Pilot programs would address the scalability of such efforts, which thus far have been modest in-school-time (Invention Education Research Group, 2019). At a broader level, (nation-)states could incorporate inventing and other human-centered engineering into existing socio-emotional learning measures. That is, the emphasis on empathic, cultural, and collaborative matters could align well with accountability around topics like self-awareness, self-management, social awareness, relationship skills, and responsible decision making (Collaborative for Academic, Social, and Emotional Learning [CASEL], 2015). While private organizations are working to fill these gaps, municipal mandates could do more to ensure equitable learning opportunities through invention education and other user-centered design, especially if adequate resources are provided to underfunded schools and districts (Invention Education Research Group, 2019; Massachusetts Institute of Technology [MIT], 2016).

Closing Remarks

This three-paper set bridges individual and social conceptions of student engagement; it unites Eastern/Western and Global North / Global South cultural positionings, as well as qualitative/quantitative methodological divides, in self-efficacy; and it expands the "outside world"/classroom duality in educational design with the Social Infrastructure Framework. Ultimately, these dialectics drive deeper understandings of the three central concepts, in both in-school-time and out-of-school-time settings, for both practitioner and researcher publications. Thus, in a realization of the equal treatment of dialectical pluralism – and working towards a more equitable approach of critical dialectical pluralism – the work continues, in a spirit of fostering more just learning environments, educational systems, and global societies.

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Appendix 1: Interview Protocols

A) Insulating-Device Project: Teacher Pre-Interview
   1) Could you tell me what major changes you've made to the curriculum?
      a) (for each major change, ask) Why did you make the changes?
   2) Do you think your students will have challenges when learning with the Chill Out unit (*Make sure the teacher will talk about challenges in both science learning and design of the shoebox*)?
      a) What are the challenges?
      b) (for each challenge, ask) What do you plan to do to help?
   3) Do you think your ELL or FLEP students will have challenges specific to them? (*Make sure the teacher will talk about challenges in both science learning and design of the shoebox*)
      a) What are the challenges?
      b) (for each challenge, ask) What do you plan to do to help?
   4) Compare this Chill Out unit with science projects such as building a roller coaster,
      a) in what ways do you think they are similar?
      b) In what ways do you think they are different?
   5) Think about your experience of implementing this unit last year, do you plan to change your teaching when teaching with the Chill Out unit?
      a) If yes, what are the changes?
   6) Last year in the post-interview you mentioned that the students were excited but you felt that there were no "eureka" moments. How do you plan to address this issue?

****

B) Insulating-Device Project: Teacher Check-In's (brief mid-interviews)
   1) What worked well the past few class sessions?
   2) What didn't work so well?
   3) What might you do differently next time?
   4) How can we from Boston College better support you moving forward?

****

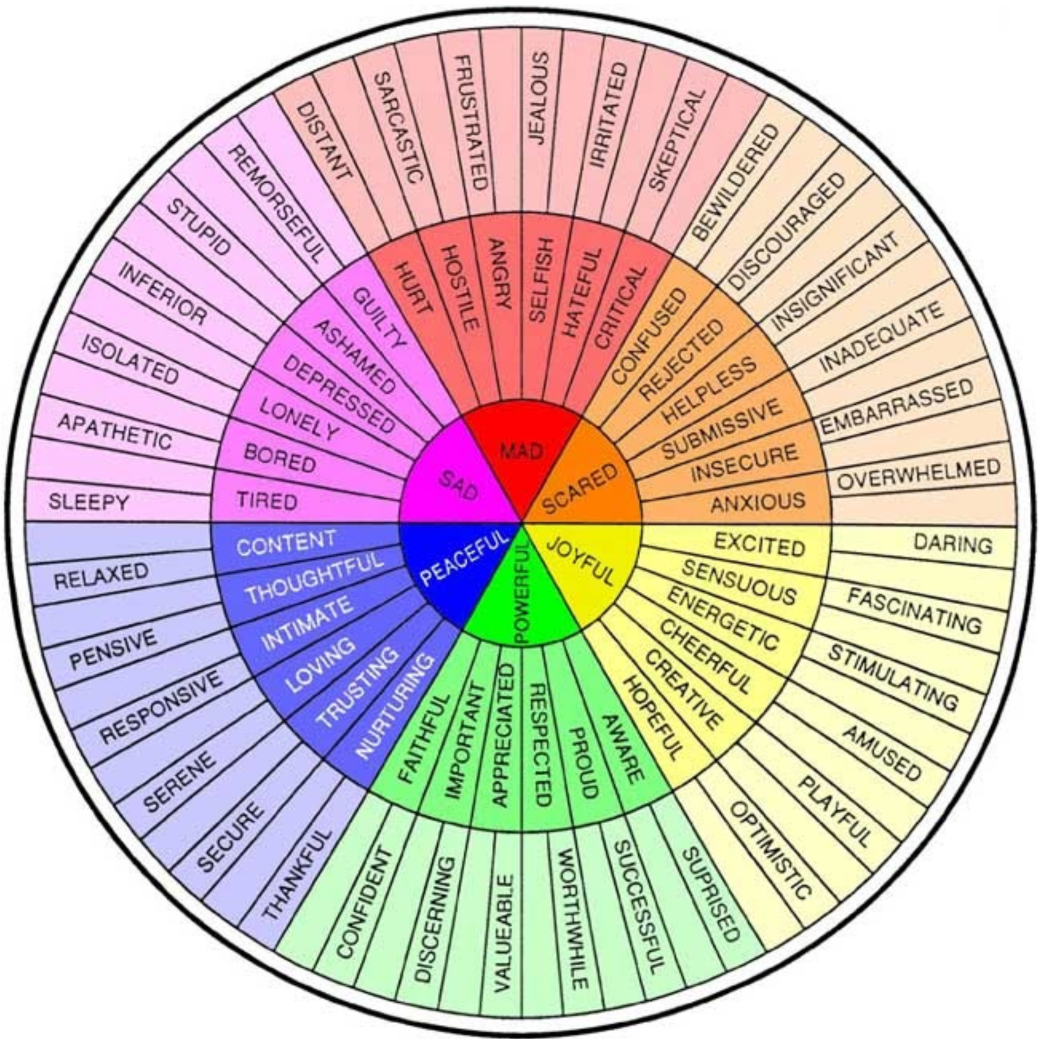
C) Insulating-Device Project: Teacher Post-Interview
   1) What is your overall impression of this classroom run of the Chill Out unit?
      a) Do you think your kids were engaged or excited? Did you see any "eureka moments"? Could you tell me an example?
   2) Think about the entire unit,
      a) what did you implement differently? Why? (Show the list of the labs and major activities of the Chill Out unit)
      b) In general do you think your teaching practices changed? Could you tell me more about it?

c) What did you learn by implementing this unit the second time?
d) Do you feel more confident in teaching these types of hands-on projects?

3) Did your students encounter any challenges during the unit?
   a) Could you share any **science** challenges students met? What did you do to help them overcome the challenges?
   b) Could you share any **invention** challenges students met? What did you do to help them overcome the challenges?
   c) Could you share any **group work** challenges students met? What did you do to help them overcome the challenges?
4) How did you organize student groups? Random? Four Corners? Or other?
5) Did you provide explicit instructions on how to collaborate? If yes, what did you provide? How did you decide what instructions to be provided?
6) In the pre-interview you mentioned that students probably will have challenges in connecting the multiple pieces in the unit, do you think your students were able to connect these pieces in this run?
   a) Where do you think students connected? Where do you think they did not?
   b) Did you do anything to help them see the big picture or the connection between heat transfer, the lunchbox invention, and the patent application? If yes, could you tell me more about it?
7) Did ELL or FLEP students experience particular challenges during the unit? What did you do to help them?
   a) You mentioned that ELLs tend to be followers in group work, could you tell me more about it? did they participate in the collaboration or did they do nothing?
   b) Can you tell me about ELLs' performance on the patent application work? How did the ELLs participate?
   c) (in the pre-interview, two challenges Mr. Braun envisioned for ELLs, participating in the group work because ELLs tend to be followers, working on the patent application)
8) Is there anything else you want to tell us?

****

D) <u>Insulating-Device Project</u>: Student Pre-Interview
   1) What does "invention" mean to you?
   2) What do you think inventors do?
   3) You're about to start an invention project. How do you think you might feel about inventing? Here are some words to help you express yourself. ***Please <u>circle</u> about 4-6 words.***



a) Why did you pick those words? Can you describe an example?
b) How anxious are you about inventing? [0 = Not anxious at all, 5 = half as anxious as I ever get, 10 = Completely Anxious]

0 1 2 3 4 5 6 7 8 9 10

not anxious — medium anxious — completely anxious

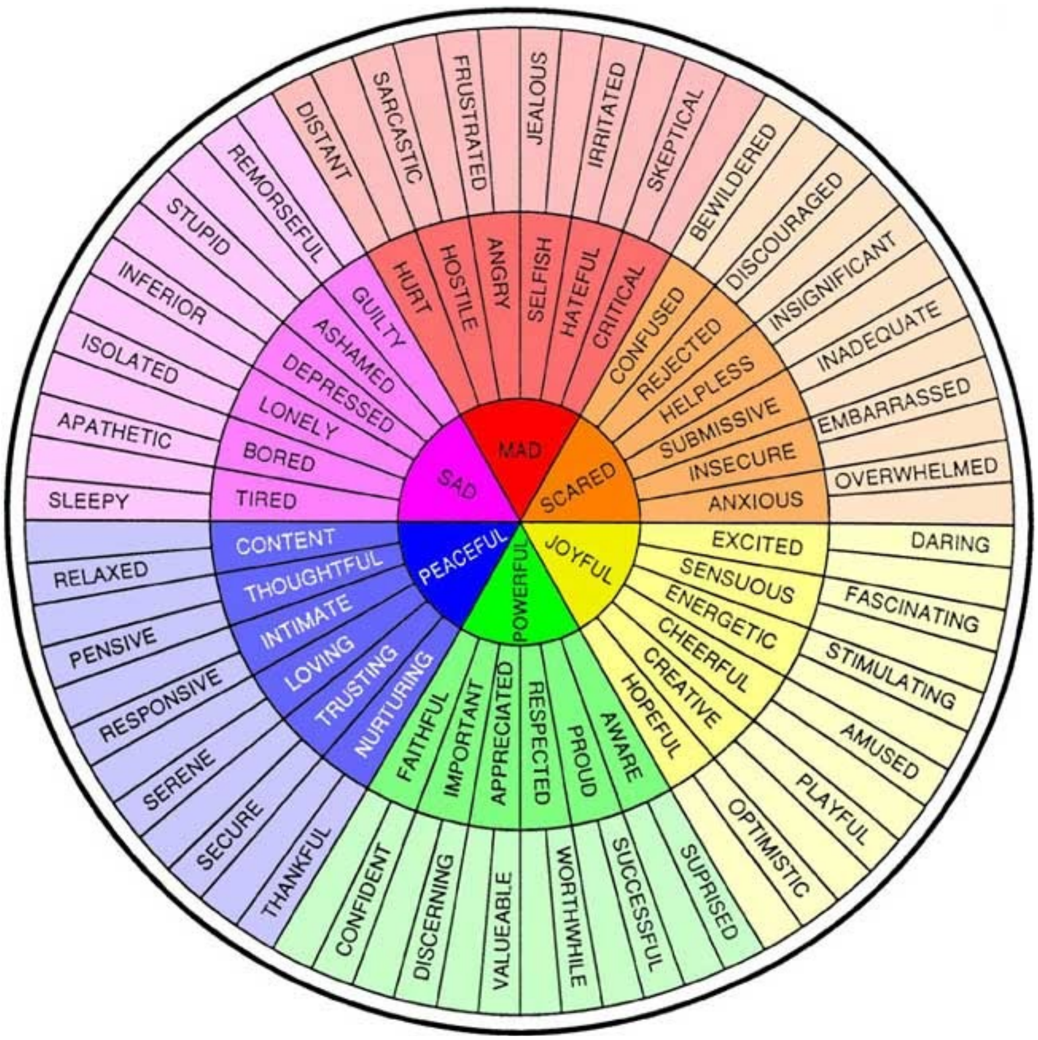
4) Please describe your experiences with group projects in science classes.
5) How do you feel about group projects for science classes?
   a) Why did you pick those words? Can you describe an example?
   b) To what extent, if at all, do you feel nervous or anxious?
6) Is there anything else you'd like to share, or any questions you have for me?

Thank you very much for your participation!

****

E) <u>Insulating-Device Project</u>: Student Post-Interview

1) What does "invention" mean to you?
2) What do you think inventors do?
3) We're curious if your feelings about **<u>inventing</u>** have changed, stayed the same, or some of both. Here is your sheet from before the project. ***Please <u>star (*)</u> about 4-6 words, which can be the same as or different than the ones you circled in December.***



a) **If you made any changes, why did you pick those words? Can you describe an example?**

b) **How anxious are you about inventing? [0 = Not anxious at all, 5 = half as anxious as I ever get, 10 = Completely Anxious]**

0	1	2	3	4	5	6	7	8	9	10
not anxious					**medium anxious**				**completely anxious**	

4) We're wondering what this project experience was like for you.
    a) Were you mostly on-task, mostly distracted, or about the same of both?
    b) Were your thoughts focused, or did they wander?
    c) Did it feel enjoyable, unpleasant, or neither ("blah", "meh", etc.)?
    d) Overall, would you say you were engaged? Why or why not?
5) How well do you think you did at <u>inventing</u> (the cell phone stand and the lunchbox)? Why do you think so?

    0 = Awful, the Worst … 10 = Excellent, the Best

0 = Worst	1	2	3	4	5 = About average	6	7	8	9	10 = Best

6) How good do you think you would be at doing <u>another</u> inventing project? Why do you think so?

    0 = Awful, the Worst … 10 = Excellent, the Best

0 = Worst	1	2	3	4	5 = About average	6	7	8	9	10 = Best

7) How much do you see yourself inventing as an adult? Why do you think so?
    0 = Never … 10 = All the Time

0 = Never	1 = Maybe once	2	3	4	5 = Sometimes	6	7 = Often	8	9	10 = All the Time

8) How is your experience with this invention project **similar** to your previous experiences with group science projects? How is it **different**?
9) Is there anything else you'd like to share, or any questions you have for me?

Thank you very much for your participation!

****

F) <u>Winter Vacation Camp</u>: New-to-JVIT Teacher Pre-Interview
    Before interview, chat with Mr. S on his background: focus on whether he was a career-changer.
    1) What does invention education mean to you in this setting?
    2) What do you think kids will learn from this U-Control unit?

3) In what ways do you think this unit is similar or different from other hands-on science projects you've done before?
4) Where do you think students may have challenges when learning with this U-Control?
    a) (for each challenge, ask) What do you plan to do to help?

****

G) <u>Winter Vacation Camp</u>: New-to-JVIT Teacher Post-Interview

1) What is your overall impression of this implementation of the U-Control unit?
    a) Do you think the kids were engaged or excited? Did you see any "eureka moments"? Could you tell me an example?
2) Now you have completed this invention education unit.
    a) What does invention education mean to you?
    b) In what ways do you think this unit is similar or different from other hands-on science projects?
3) Do you think your teaching of this unit is similar or different from your teaching of other hands-on science projects?
    a) What are the similarities?
    b) What are the differences? Could you tell me some examples? For each example, did the different teaching strategies make your teaching more effective? Why?
    c) Do you feel more confident in teaching these types of hands-on projects?
4) Do you envision using invention education in your classroom?
    a) What challenges do you think teachers might encounter in a classroom setting?
    b) Is there any that you've done in the camp can be transferred into the classroom setting?

****

H) <u>Winter Vacation Camp</u>: Experienced-with-JVIT Teacher Post-Interview

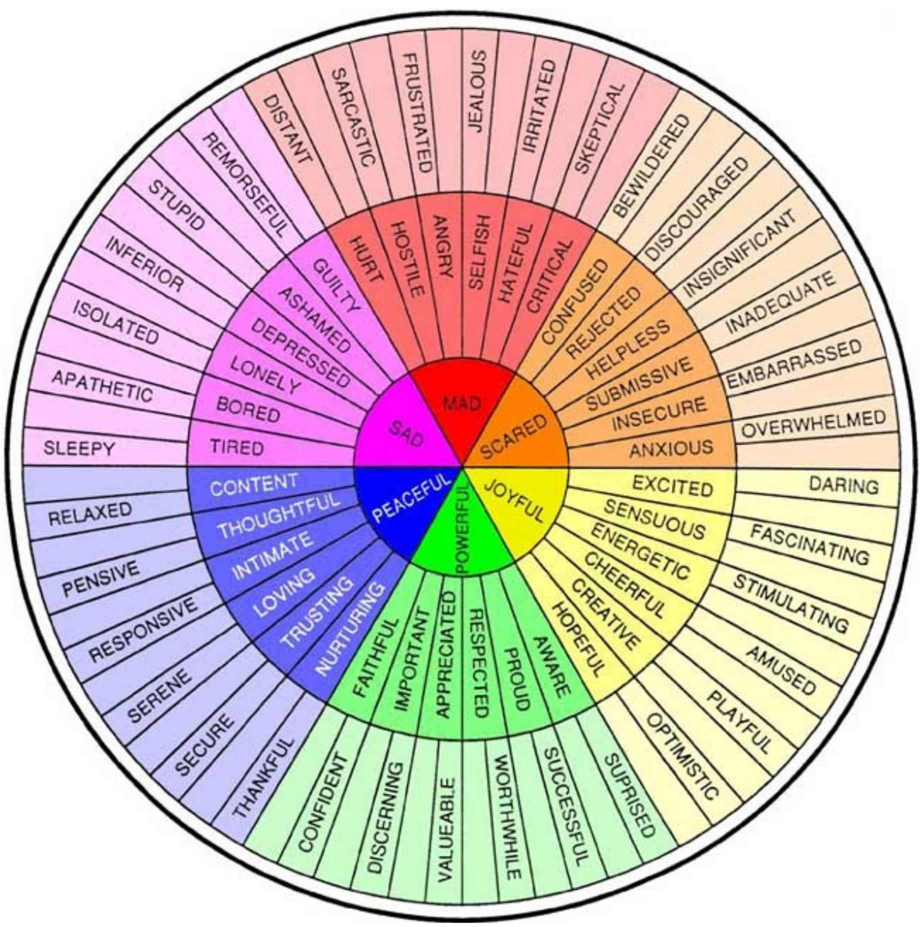
1) You have used the invention education curriculum a few times, could you tell me what units, when, and under what settings did you use them? (Chill Out, E-Textile, Going Green, ???)
2) What does invention mean to you?
3) How did you implement the activities of the U-Control unit?
4) How does implementing invention education in out-of-school settings differ from teaching it in classrooms?
5) Now you have used invention education in school and out of school.
    a) Is there anything you have done in school that can be used in afterschool? Or vice versa?
    b) What are important strategies to teach invention in school? In afterschool?

****

I) <u>Winter Vacation Camp</u>: Camper Pre-Interview

1) Please describe your experiences with group projects in science classes.

2) In general, how engaged are you with **science classes**? Why you think that you were that engaged? (*Probe: Engagement means that what you're doing, thinking, and feeling is on-task / on-topic.*)
   a) Have you mostly stayed on-task, mostly been distracted, or about the same for both? Why do you think that is?
   b) Have your thoughts been focused, or do they wander? Why?
   c) Have science classes felt enjoyable, unpleasant, or neither ("blah", "meh", etc.)? Why?
3) In general, how engaged are you with **group projects** in science classes? Why you think that you were that engaged? (*Probe: Engagement means that what you're doing, thinking, and feeling is on-task / on-topic.*)
   a) Have you mostly stayed on-task, mostly been distracted, or about the same for both? Why do you think that is?
   b) Have your thoughts been focused, or do they wander? Why?
   c) Have science classes felt enjoyable, unpleasant, or neither ("blah", "meh", etc.)? Why?
4) How do you **feel** about your past group projects in science classes? Please choose 4-6 words from the "feelings wheel" below (by Gloria Willcox), or choose your own words.



   a) **Why did you pick those words? Can you describe an example?**

5) Grades 7-8 only (*if grade 6, then skip to question VI)*:
   a) From the ***Chill Out* unit during school time**, what knowledge and skills did you use when inventing?
      (i) What knowledge and skills from **outside of science class** did you use?
         (a) Probe: Different subjects, clubs, activities, teams, etc.
      (ii) What knowledge and skills from **outside of school** did you use?
         (a) Probe: Family, friends, neighbors, etc.

   <If already at 10 minutes, skip B, C, D below, and go to question VI.>

   b) From the ***Chill Out* unit during school time**, what do you remember about the Types of Team Members?
      (i) *Reminder, if needed: Doodler, Organizer, Talker, and Tinkerer*
      (ii) Probing #1: Which role were **you** assigned?
      (iii) Probing #2: How did you feel about being in that role? Why?
      (iv) Probing #3: How much did you stay within that role, compared to how much you took on other roles?
   c) Now let's think about your **teammates** during *Chill Out*.
      (i) How much did **your teammates** stay within their roles, compared to how much they took on other roles?
      (ii) What, if anything, caused them to change roles?
6) What do you think are some strengths and weaknesses of using Types of Team Members for invention teams?
   a) Probing #1: What did it feel like, to have assigned roles?
   b) Probing #2: Do you think it helped your team work better, worse, some of both, or did it make no difference?
7) Do you have anything else you'd like to share, or any questions for me?
   Thank you very much for your participation!

****

J) Winter Vacation Camp: Camper Check-In's (brief mid-interviews at 11:55 AM & 2:25 PM)
   1) I'm curious about if the project is keeping your thoughts, feelings, and actions focused.
      a) thoughts [cognitive]:
      b) feelings [affective/emotional]:
      c) actions [behavioral]:
   2) I noticed that your group changed some roles.
      a) How did your group decide that changing roles would be good to ***consider*** (i.e., to *think* about doing)?
      b) How did your group decide that changing roles would be good to ***do***?
      c) What knowledge and skills did you think were important for different roles?
   3) Did you feel that the role you were assigned had an impact on how much you could participate? Why or why not?
      a) *Probing: Does it seem pretty balanced, or are there times when some teammates are participating more than others?*

4) Do you have anything else you'd like to share, or any questions for me?
   Thank you very much! Enjoy your lunch time / Enjoy the rest of your day!

****

K) Winter Vacation Camp: Camper Post-Interview

1) How engaged have you been in this project, and why you think so? (*Probe: Engagement means that what you're doing, thinking, and feeling is on-task / on-topic.*)
   a) Have you mostly stayed on-task, mostly been distracted, or about the same for both? Why do you think that is?
   b) Have your thoughts been focused, or do they wander? Why?
   c) Have science classes felt enjoyable, unpleasant, or neither ("blah", "meh", etc.)? Why?
2) How is your experience with this invention project **similar** to your previous experiences with **group science projects**? How is it **different**?
3) How is your experience with this invention project **similar** to your previous experiences with **science class in general**? How is it **different**?
4) From the ***U Control*** **unit this week**, what knowledge and skills did you use when inventing?
   a) What knowledge and skills from **outside of science class** did you use?
      (i) Probe: Different subjects, clubs, activities, teams, etc.
   b) What knowledge and skills from **outside of school** did you use?
      (i) Probe: Family, friends, neighbors, etc.
5) From the ***U Control*** **unit during February vacation**, what do you remember about the Types of Team Members?
   a) Reminder, if needed: Doodler, Organizer, Talker, and Tinkerer
   b) Probing #1: Which role were you assigned?
   c) Probing #2: How did you feel about being in that role? Why?
   d) Probing #3: How much did you stay within that role, compared to how much you took on other roles?
6) If you had to do the project again, would you choose the same role(s)? Why or why not?
   <If already at 15 minutes, skip 7 & 8 below, and go to question 9.>
7) Now let's think about your teammates during *U Control*.
   a) How much did **your teammates** stay within their roles, compared to how much they took on other roles?
   b) What, if anything, caused them to change roles?
8) What do you think are some strengths and weaknesses of using Types of Team Members for invention teams?
   a) Probing #1: What did it feel like, to have assigned roles?
   b) Probing #2: Do you think it helped your team work better, worse, some of both, or did it make no difference?
9) Do you have anything else you'd like to share, or any questions for me?
   Thank you very much for your participation!

Appendix 2: Survey Protocols

A) <u>Insulating-Device Project</u>: Student survey protocol
**Questions 1-8 were on the pre-, mid-, and post-surveys.*
**Questions 9-25 were on the pre- and post-surveys (but NOT mid-surveys).*

How much do you agree? [strongly disagree / disagree / neutral / agree / strongly agree]

1) I can make something useful out of material like cardboard, wood, or fabric.
2) I can use tools such as thermometers and utility knives.
3) I can work as part of an invention team.
4) I can test the thermal insulating and conducting properties of various materials.
5) I can demonstrate heat transfer.
6) I can build a portable cooling device.
7) I can identify a real-world problem to solve.
8) I can apply my skills to solve a real-world problem.
9) I can make something that helps people.
10) I can make something that people want to use.

11) How good do you think you would be at doing another inventing project?
0 = Awful, the Worst ... 10 = Excellent, the Best

How much do you agree? [strongly disagree / disagree / neutral / agree / strongly agree]

12) When I hear the word "inventing" I have feeling of dislike.
13) I feel tense when someone talks to me about inventing.
14) It makes me nervous to even think about inventing.
15) It scares me to have to take an inventing class.
16) I have a good feeling toward inventing.

17) How anxious are you about inventing? ***0 = Not at all ... 10 = Completely***

To what extent are you like these people? [strongly disagree / disagree / neutral / agree / strongly agree … i.e., *that you are like them*]

18) Kiara doesn't want a job as an inventor because she has no interest in it.
19) Chris would like a job as an inventor.
20) Anna would TRY a job as an inventor if it was easy to do.
21) Helena would be willing to study for 2 years after high school to become an inventor.
22) Jose seeks out online videos to learn about inventing.
23) Tomas can NOT stop doing something else he likes, in order to work on invention instead.

24) Ruth spends most of her free time working on inventions.

25) How much do you see yourself inventing as an adult? *0 = Never ... 10 = All the Time*

****

< Winter Vacation Camp survey protocols begin on the following page. >

B) Winter Vacation Camp: Student survey #1

Name: ______________________________ Date: February 18, 2019

STUDENT SELF-ASSESSMENT: U CONTROL

Inventors need to be confident and know their own strengths and weaknesses. Use this table to think about how likely you are to complete these skills with confidence. Check the response that best describes your confidence right now.

	strongly agree	moderately agree	slightly agree	neutral	slightly disagree	moderately disagree	strongly disagree
I can use electrical circuits to change how a motor performs.							
I stay focused in vacation camp.							
I have enjoyed learning new things in vacation camp.							
I can work in MANY different ways on my own invention project.							
I thought about different ways to solve a problem in vacation camp.							
I pay more attention in vacation camp than I do in school science.							
I can work in MANY different ways as part of an invention team.							
I can apply my understanding of electromagnetism to build an electric door.							

What knowledge and skills from outside of camp did you use today?

In the Future

What will YOU invent?

____

How is it unique?

____

How is it useful?

____

UC_E083016 P17

****

C) Winter Vacation Camp: Student survey #2 (also used as #4)

Name: ______________________________ Date: February 19, 2019

STUDENT SELF-ASSESSMENT: U CONTROL

Inventors need to be confident and know their own strengths and weaknesses. Use this table to think about how likely you are to complete these skills with confidence. Check the response that best describes your confidence right now.

	strongly agree	moderately agree	slightly agree	neutral	slightly disagree	moderately disagree	strongly disagree
I can apply my understanding of electromagnetism to build an electric door.							
I pay more attention in vacation camp than I do in school science.							
I thought about different ways to solve a problem in vacation camp.							
I can work in MANY different ways on my own invention project.							
I have enjoyed learning new things in vacation camp.							
I stay focused in vacation camp.							
I can work in MANY different ways as part of an invention team.							
I can use electrical circuits to change how a motor performs.							

Types of Team Members: Today, how much were you…

	almost always	often	sometimes	rarely
doodling				
organizing				
talking				
tinkering				
doing something else				

What knowledge and skills from outside of camp did you use today?

UC_E083016 P17

****

D) <u>Winter Vacation Camp</u>: Student survey #3 (also used as #5); reordered some items

Name: ______________________________ Date: February 20, 2019

STUDENT SELF-ASSESSMENT: U CONTROL

Inventors need to be confident and know their own strengths and weaknesses. Use this table to think about how likely you are to complete these skills with confidence. Check the response that best describes your confidence right now.

	strongly agree	moderately agree	slightly agree	neutral	slightly disagree	moderately disagree	strongly disagree
I can use electrical circuits to change how a motor performs.							
I stay focused in vacation camp.							
I have enjoyed learning new things in vacation camp.							
I can work in MANY different ways on my own invention project.							
I thought about different ways to solve a problem in vacation camp.							
I pay more attention in vacation camp than I do in school science.							
I can work in MANY different ways as part of an invention team.							
I can apply my understanding of electromagnetism to build an electric door.							

Types of Team Members: Today, how much were you…

	almost always	often	sometimes	rarely
doodling				
organizing				
talking				
tinkering				
doing something else				

What knowledge and skills from outside of camp did you use today?

UC_E083016 P17

Appendix 3: Observation Protocols

A) <u>Insulating-Device Project</u>: Student-team observation protocol

Observation Protocol: *Chill Out* 2018 (**Take a picture of every version of the design!!)**

Teammates' Names________________________________ Observer name________________ Date __________

<u>RQ</u>: How and in what ways do participation structures promote and/or restrict student engagement in a team-based invention project?

Time	*Notes on student engagement (affective, behavioral, cognitive)*	*Notes on role **performance** (Doodler, Organizer, Talker, Tinkerer)*	*Notes on role **negotiation*** (Who/what determined when to change roles?)	Other notes about the **team** (~3-5 students)	Other notes about the **full class** (~20-25 students)

Reflection *(continue notes and/or reflection on the next page/s if needed)*:

- In what way(s), if any, did roles seem to **promote** student engagement?

- In what way(s), if any, did roles seem to **restrict** student engagement?

****

B) Winter Vacation Camp: Student-team observation protocol

Observation Protocol: *U Control* 2019 (**Do check-in's at 11:55 and 2:25!)**

Teammates' Names___________________________ Observer name______________ Date _________

RQs:
- How does the participation of students working in small groups evolve over time during an invention camp?
- What are the affordances and limitations of providing participation structures, with regard to student engagement?
- What sense-making resources do students from ethnically, culturally, and linguistically diverse communities employ as they take these roles?
- What is the nature of the relationship between these resources and students' roles in the participation structures? How do researchers and teachers make this relationship visible?

Time	*Notes on student engagement (emotional, behavioral, cognitive)*	*Notes on roles (Doodler, Organizer, Talker, Tinkerer,* <anything else?>*)*	*Notes on sense-making resources*	Relationship between roles and resources	Other notes

Check-in (at 11:55 and 2:25) → audio-record this!
- I noticed that your group changed some roles.
  - How did your group decide that changing roles would be good to ***consider*** (i.e., to *think* about doing)?
  - How did your group decide that changing roles would be good to ***do***?
  - What knowledge and skills did you think were important for different roles?
- Did you feel that the role you were assigned had an impact on how much you could participate? Why or why not?
  - *Probing: Does it seem pretty balanced, or are there times when some teammates are participating more than others?*
- Do you have anything else you'd like to share, or any questions for me?
- Thank you very much! Enjoy your lunch time!

Observer Reflection *(continue notes and/or reflection on the next page/s if needed)*:

- How did the participation of students working in small groups evolve *during this observation*?
- What conjectures can you make about participation structures and student engagement?
- What sense-making resources did students employ in their roles?
- What conjectures can you make about sense-making resources and students' roles? How did researchers and teachers make this relationship visible?

Appendix 4: Supplemental Tables

Table S1

Disaggregated Demographics to the Insulating-Device Project (IDP)

	gend.*		
Race/Ethnicity	f	m	all
Latinx	9	6	15
Latinx + White	2	3	5
Latinx + Black, African, African-American	1	1	2
Latinx + Black, Caribbean + White	1		1
Latinx + Cape Verdean + White	1		1
Latinx total	14	10	24
Black, African, African-American	2	2	4
Black, Caribbean		3	3
Latinx + Black, African, African-American	1	1	2
Latinx + Black, Caribbean + White	1		1
Latinx + Cape Verdean + White	1		1
Black, African, African-American + White		1	1
Black, African, African-American + Black, Caribbean + Asian + South Asian + Native American or Pacific Islander		1	1
Black, African, African-American + Middle Eastern/North African	1		1
Black total	6	8	14
White	19	13	32
Latinx + White	2	3	5
White + Middle Eastern/North African		2	2
Latinx +Black, Caribbean + White	1		1
Latinx + Cape Verdean + White	1		1
Black, African, African-American + White		1	1
White Total	23	19	42
Middle Eastern/North African	1	2	3
Black, African, African-American + Middle Eastern/North African	1		1
Middle Eastern/North African + South Asian		1	1
Middle Eastern/North African total	2	3	5
South Asian	3	2	5
Central Asian	1		1
Middle Eastern/North African + South Asian		1	1
Black, African, African-American + Black, Caribbean + Asian + South Asian + Native American or Pacific Islander		1	1
South Asian & Central Asian total	4	4	8
No Response	2	1	3
Grand Total	41	39	80

**Notes.* While there was a non-binary gender category, no students chose it. Six students did not complete any of the pre-survey. Table is used with permission from Jackson and Semerjian (2020).

Table S2

Detailed Results of Exploratory Factor Analyses

Items: *I can…*	Factor 1	Factor 2
…test the thermal insulating and conducting properties of various materials.	.748	.164
…demonstrate heat transfer.	.703	.133
…build a portable cooling device.	.623	.180
…work as part of an invention team.	.474	.192
…make something useful out of material like cardboard, wood, or fabric.	.368	.292
…use tools such as thermometers and utility knives.	.367	.209
…apply my skills to solve a real-world problem.	.119	.965
…identify a real-world need.	.348	.577

Table S3

Detailed Results of Reliability Analysis

Items: *I can…*	**Scale Mean if Item Deleted**	**Scale Variance if Item Deleted**	**Corrected Item-Total Correlation**	**Squared Multiple Correlation**	**Cronbach's α if Item Deleted**
…make something useful out of material like cardboard, wood, or fabric.	25.77	19.796	.434	.228	.774
…use tools such as thermometers and utility knives.	25.35	19.502	.386	.158	.783
…work as part of an invention team.	25.47	19.027	.463	.240	.770
…test the thermal insulating and conducting properties of various materials.	26.05	18.470	.595	.488	.749
…demonstrate heat transfer.	26.03	18.750	.550	.431	.756
…build a portable cooling device.	26.02	18.004	.536	.351	.758
…identify a real-world need.	25.65	18.542	.534	.439	.758
…apply my skills to solve a real-world problem.	25.68	19.476	.462	.415	.770

Note. For the complete subscale of all eight items, Cronbach's α=.788

Appendix 5: Supplemental Figures

Figure S1

Self-efficacy Development through Cognitive Processes about Ability