Teachers Learning to Prepare Future Engineers

A Systemic Analysis Through Five Componments of Development and Transfer

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Abstract

This study used a systemic perspective to examine a five-component experiential process of perceptual and developmental growth, and transfer-to-teaching. Nineteen secondary math and science teachers participated in a year-long, engineering immersion and support experience, with university faculty mentors. Teachers identified critical shifts in perceptions of engineering, and recognized appropriateness of engineering as a career option for their students. They transferred

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content learning and perceptions to students, through experiential narratives and instructional activities. Teachers reported that their secondary math and science students demonstrated observable change in knowledge, skill and beliefs about engineering, subject area score and skill improvement, class engagement, and engineering-related career aspirations.

Introduction

According to the U.S. Department of Education (2015), "only 16 percent of American high school seniors are proficient in math and interested in a STEM career." The United States is suffering a shortage of engineers and similar skilled professionals (National Academy of Sciences, 2007). Because interest in such careers begins foundationally in elementary and secondary schools (Sheppard, Macatangay, Colby, & Sullivan, 2009), teachers in the United States are expected to educate and motivate youths toward careers in science, technology, engineering, and mathematics (STEM) professions (National Academy of Sciences, 2007). These efforts are hampered by the unfamiliarity of most math and science teachers with STEM careers. Engineering has particular appeal to address this need, because it combines and integrates math, science, and technology knowledge and skills in concrete, applied projects with intuitive value and utility for teachers and students and includes the equally valued skills of collaboration and team-based project development. Meaningful, authentic engineering-based experiences can help teachers meet challenges to educate and motivate their students about STEM career fields like engineering.

Because understanding the roles and responsibilities of the engineering professions and being able to teach to this depth go beyond mere content knowledge and simple skills to include culture and context, teachers' engineering experience is enriched by including STEM acculturation and identity development (National Science Foundation, 2009). In addition, research from such programs needs to demonstrate fully the pathways of effects from teachers' to students' learning. The need to bridge from elementary and secondary school math and science to postsecondary STEM careers like engineering is not only a U.S. concern but an international one (Clark & Andrews, 2010). Worldwide, nations are concerned about students' interest and engagement in STEM courses and careers (Woods-McConney, Oliver, McConney, Schibeci, & Maor, 2014). Promoting such engagement requires developing teachers' knowledge and skill, along with their pedagogical ability to cultivate STEM knowledge and skill in their students (Hackling, Peers, & Prain, 2007).

Background/Literature Review

Leaders in the United States are concerned because the nation's economic health and technological innovation depend on engineering (Atman, Kilgore, & McKenna, 2008), and the current shortage of professional engineers is exacerbated by high attrition in engineering programs (Accreditation Board for Engineering and Technology, 2012). In addition, the United States often falls behind in worldwide comparisons of school-aged children's math and science engagement, knowledge, and literacy (Daugherty & Custer, 2012). In response, the U.S. government has initiated a number of broad initiatives and allocated substantial resources to promote STEM education in elementary and secondary schools (U.S. Department of Education, 2015). Engineering presents authentic opportunities to demonstrate the practical value and utility of math and science, supporting students' motivation to learn math and science (National Science Foundation, 2010). Educating teachers about engineering so that they can educate their students can strengthen the educational pipeline to skilled science professions like engineering. Research is needed on processes and supports that help teachers understand the interdisciplinary field of engineering and integrate that understanding into their teaching. This pathway of inquiry was the focus of the present study.

Perceptions Influence Teacher Learning and Development

Learning and understanding depend on cognitive processing (gaining information and ideas) plus perceptions about that knowledge and skills in domains (Hardré & Sullivan, 2008). Perceptions of self, information, and the relationships between them drive identity development and enhance or disrupt learning, apart from characteristics such as subject-area aptitude and even general ability (Dweck, Mangels, & Good, 2004). Many teachers perceive engineering as abstract, complex, and difficult to learn and lack efficacy for it themselves (Hardré, Nanny, Refai, Ling, & Slater, 2010), so they hesitate to introduce engineering to their students (Musanti & Pence, 2010). Perceptual change regarding engineering can refine teachers' understanding, replacing negative perceptions with positive perceptions and productive motivations. This paradigm shift can be facilitated through positive, authentic experience; effective role models; and a supportive, collaborative community of mentors and peers (Brand & Moore, 2011; Dresner & Worley, 2006). These features were designed into the teachers' learning environment for this project.

Social Dynamics Influence Teacher Development

High-quality, sustained teacher professional development involves multiple dimensions of interpersonal relatedness, social support and influence, networking and communication, and social risk and vulnerability. Shifting teachers' social and experiential perspectives to learner roles can impact perceptions and consequent instructional practice (Battey & Franke, 2008; Musanti & Pence, 2010). Learning novel skills in unfamiliar domains such as engineering requires teachers to admit lack of expertise, which involves social risk and vulnerability and opens doors to change (Dresner & Worley, 2006; Duderstadt, 2008). Enduring educational change requires teachers' exposure to relevant knowledge along with social support as they embrace new ideas and see how to transfer them to practice (Baker-Doyle & Yoon, 2011; Duke, 2004). Teacher development with these characteristics can enable teachers to cross traditional boundaries and expose their students to innovative educational opportunities.

Motivation Influences Teacher Development

Like anyone else, teachers effectively transfer learning from unfamiliar fields only with effort and persistence, supported by personally valued and internalized motivations and developmentally supportive communities in their learning and work environments (Borko, 2004; Charness, Tuffiash, & Jastrzembski, 2004). Teachers' motivation is supported by perceptions that they can learn new skills well and that knowing them will be important for their students (Barnes, Hodge, Parker, & Koroly, 2006). These critical perceptions can be promoted through motivational support explicitly designed into teachers' professional development (Hardré et al., 2013). Motivation powerfully promotes teachers' learning, skill development, and transfer (Powell-Moman & Brown-Schild, 2012). Such systematic research can contribute to deeper understanding of how teachers' cognitive, motivational, and social characteristics interact in a complex systemic and social dynamic during professional development experiences.

Context and Community Influence Teacher Development

University research laboratories are contextually and culturally novel learning environments for most teachers, and that novelty contributes to the potential for dramatic development (Hardré et al., 2013). Novelty of context and culture can prompt openness and metacognitive awareness, which support acculturation and shared discourse development, forming foundations for an interdisciplinary learning community (Dresner & Worley, 2006; Robbins & Aydede, 2009). Such experiences promote professional identity development and transformation in teacher practice (Hardré et al., 2014; Hardré et al., 2013).

Teachers' professional identities are shaped by learning experiences situated within specific contexts, enabling them to internalize meaning and value from activities and relationships with their teachers and mentors (Brown & Melear, 2007; Hanegan, Friden, & Nelson, 2009; Lenz & Lange, 2005). Like most people, teachers are generally most comfortable working with similar others, yet greater innovation and development result from interactions among people with different skills and perspectives (Borgatti & Foster, 2003; Downey et al., 2006). Math and science teachers working together develop unique products and perspectives beyond their usually single-subject workspaces (Basista & Mathews, 2002), with benefits even more dramatic when they collaborate with engineers in the novel, authentic context of the engineering lab (Brand & Moore, 2011; Smith & Conrey, 2009).

Situated Inquiry-Based Learning Influences Teacher Development

A key to the engineering context is its dynamic use of inquiry-based learning in contrast to traditional, transmission-type teaching. Inquiry focuses on conceptual understanding (in contrast to fact learning), underscoring the utility and relevance of science (Cobern, Gibson & Underwood, 1999; Linn & His, 2000). Learners engage in active questioning, make reasoned decisions, use resources to solve problems, and thus develop understanding of how science works in the world (Donham, 2010). Inquiry-based learning environments are learner centered and motivating (Kubicek, 2005), promoting deeper conceptual understanding and scientific literacy (Seraphin, Philippoff, Kaupp, & Valin, 2012), more general reasoning and critical thinking skills (Trowbridge, Bybee, & Powell, 2004), and social bonding (Wolf & Fraser, 2008). The National Science Educational Standards state that "inquiry is central to science learning" (National Research Council, 1996, p. 2).

Situated learning considers authentic context a substantive element of instruction and learning (Lave & Wenger, 1991; Robbins & Aydede, 2009). More authentic tasks and contexts, with appropriate supports, produce more effective learning (Hardré et al., 2013; Sawyer & Greeno, 2009). Mentors in this project gave their teacher learners high autonomy, supporting inquiry-based learning, while also explicitly exposing their expert reasoning within authentic engineering research labs. This integrative instructional approach was designed to support learners' development of understanding of professional engineering tasks and skills and to promote familiarity with how engineers think and reason. Authentically situated engineering projects are hands-on, physically and mentally active task characteristics that neurologically support learning and development (Sousa, 2010).

Framing the Present Study

This study investigated secondary teachers' experiences in a multievent engineering-based development opportunity that included support and follow-up for their transfer and integration to practice. Drawing from the research and theory of practice, this study operated on three premises: (a) Teachers' developmental experiences are complex interactions among cognitive, motivational, and perceptual factors; (b) teachers' learning and motivation are deeply integrated, reciprocal, and interactive; and (c) teachers' learning and transfer to practice are authentically situated in social and experiential contexts, characterized by nonlinear relationships within unique and dynamic networks of influence.

The specific framework of developmental processes in this study explored the following research questions regarding the nature of teachers' professional development that supports classroom transfer:

1. What personal and professional goals and interests did these teachers bring to their professional development experiences? These are important

to understand, because learners' goals and interests influence what they attend to, engage in, and put forth effort to learn.

2. How do teachers' engagement and effort (individually and in community) influence what they gain from professional development, in knowledge and skill learning, as well as perceptual and conceptual change?

3. What changes occurred in these teachers' learning and development, including cognitive and perceptual (internal), motivational–behavioral (externally observable), and conceptual–behavioral (actionable) change?

4. How did teachers' learning and development influence their transfer of knowledge and skills from professional development as evident in their change of practice?

5. What effects of teacher transfer are evident in observable changes in their students' perceptions, achievements, and aspirations?

The conceptual process of teacher development that underlies this study is represented in Figure 1.

Methods

Study Design

This study examined data from 19 secondary teachers in a yearlong professional development and support experience. Teachers were recruited via e-mail invitations using addresses from lists of math and science teachers gathered from school Web sites. Teachers were invited to apply to the program by filling out a form that included an essay about why they wanted to participate. Only 4 of the 19 teachers knew each other slightly prior to the program start, 2 from having attended a previous professional development event together and 2 others from serving together in a community service activity. None of them had worked closely together for long periods or currently taught in the same school.

Mixed-method data collection included direct assessment (questionnaires and journals), evaluation and observation by mentors, and interactive dialogue in an online discussion forum, tracking perceptual and behavioral development. Analyses

Figure 1

Conceptual map of RET influence in teacher development and practice.

examined multiple, independent sources of data, both quantitative and qualitative, for evidence of this process, including its dependencies. Data from multiple, independent sources were blinded as much as possible to maintain response independence.

Intervention Design

The teacher professional development experience began with a 6-week university-based, resident, mentored immersion experience in engineering, followed by at-home support for transfer to secondary classrooms. It was funded by the National Science Foundation's Research Experience for Teachers (RET) program.

On-site. Teachers collaborated on activities and projects, in small (lab) and large (cohort) groups, receiving continuous questioning and feedback from peers and mentors to engage critical thinking and promote applied skill development and transfer. Teachers worked in engineering laboratories supervised and mentored by university engineering faculty members. The projects, equipment, and tasks in each lab differed based on the nature of authentic professional work across the mentors' engineering disciplines. Teacher groups engaged in open-ended, engineering-related research projects on topics of interest using available resources and expertise. Small lab groups worked together with mentors every day, and the large group met at least weekly for discussions, workshops, and presentations. Mentors taught and modeled inquiry-based teaching of engineering so teachers could see it operationalized and experience its benefits. In addition to engaging with teachers in their labs, engineering mentors discussed with teachers how they could translate and transfer the engineering principles for their math and science classes.

Off-site. After returning home, teachers wrote proposals for projects transferring engineering principles to their classes, receiving small grant funding to cover necessary equipment and materials. Their class projects could range from controlled (lab-type) experiments to more integrated transfer across multiple topics and activities. During planning, contact with mentors was digital and asynchronous, via e-mail and discussion boards. Proposals were submitted digitally, evaluated by mentors, given feedback, revised as needed, funded, and implemented in the teachers' secondary schools.

Participants

Teachers. Participants were 19 public school math and science teachers (3 math, 16 science) who taught secondary math and science courses from basic to advanced levels (e.g., algebra, geometry, trigonometry, calculus, physical science, chemistry, biology, physics). They worked in two urban, three suburban, and seven rural districts within a 320-mile radius of the university campuses and had from 2 to 27 years of teaching experience ($M = 14$). Teachers included 8 men and 11 women aged 27–64 years ($M = 45$). As to highest level of education, 11 had bachelor's degrees and 8 had master's degrees; 16 self-identified as Caucasian, 2 as Asian, and 1 as African American. Teachers were paid room and board while on-site and were given a small stipend for their yearlong participation.

Engineering mentors. Six university engineering faculty members with earned doctorates served as mentors. They specialized in the following engineering areas: environmental (n = 1), industrial (n = 2), computer (n = 1), chemical (n = 1), and civil (n = 1). Mentors numbered four men and two women with 9–27 years of postsecondary teaching experience and 3–7 years of experience mentoring teachers. Teacher–mentor matches were made based on teachers' interests as expressed in their applications.

Data Collection

Data collection system and methods. An education faculty member and a graduate student, both trained in educational program evaluation, carried out data collection and monitoring. They used multilevel, multisource, mixed-method data and strategies and triangulated multisource results to verify findings (Johnson & Christensen, 2014; Reynolds, Livingston, & Willson, 2006; Thornkildsen, 2005). Participants were blinded from others' responses, except where the research design required access for collaboration and feedback. Data for the 19 participants were generated from 24 separate formal interactions over the full yearlong cycle of program activities, as shown in Table 1. In addition, participants initiated multiple informal contacts and communication events, which were documented in the qualitative (journal and discussions) data.

The central learning management system (LMS) served as a data collection and communication hub for questionnaires, discussions, journals, and performance measures. Data collection events were a combination of face-to-face activities and both synchronous and asynchronous digital interactions, facilitating ongoing communication and feedback.

Measures

Teacher data sources included questionnaires, journals, discussions, documentation from program activities, and teachers' project proposals and reports. Mentor data sources included discussion entries and teacher participation and project evaluations.

Questionnaires. Questionnaires had been used in similar previous studies with these participant groups (7-point Likert-type scale ranging from 1 [*strongly disagree*] to 7 [*strongly agree*]). Subscales demonstrated high reliabilities ($\alpha \geq .80$) and high test–retest consistencies (Hardré et al., 2013). They included both positively and negatively worded items to identify any agreement bias (Creswell, 2003; DeVellis, 2003). Teachers completed the perceptions questionnaires four times, as shown

Table 1
Timeline of Program and Data Collection Activities

	Program activities	*Data collection events*
Week 1	Whole-cohort meeting Orientation, LMS training Work in lab and research groups	Digital Questionnaires (intro) Discussion 1: teacher writing prompts
Week 2	Work in lab and research groups Pedagogy Workshop I	Launch journals (ongoing) Discussion 2: teacher writing prompts Discussion 3: mentor writing prompts
Week 3	Work in lab and research groups Cohort Research Conference I	Perceptions Questionnaires (Time 1) Discussion 4: teacher writing prompts
Week 4	Pedagogy and Proposal Workshops Begin project planning Work in lab and research groups	Discussions 5 and 6: develop project ideas Mentors document observations
Week 6	Cohort Research Conference II Engineering as a Profession seminar Work in lab and research groups	Perceptions Questionnaires (Time 2) Discussion 7: mentor writing prompts
	Teachers return home	
Week 7	Continue developing project planning	Discussion 8: share and feedback on project ideas
Weeks 8–10	Write project proposals	Discussion 9: continue discussion of projects
Week 11	Submit project proposal	E-mail or LMS Dropbox
Week 14	Mentor feedback on proposals	Digital rubrics to e-mail or LMS Dropbox
	Teachers return to school	
Week 18	Projects funded Teachers acquire resources	Discussion 10: teacher writing prompts Discussion 11: mentor writing prompts
Week 20	Begin implementing projects	Perceptions Questionnaires (Time 3)
Week 30	Continue implementing projects	Perceptions Questionnaires (Time 4) Continue open discussion of implementation
Week 35	Continue implementing projects Analyze data for project results	Discussion 12: teacher writing prompts Discussion 13: mentor writing prompts
Week 40	Write project reports	Continue open discussion of implementation
Week 45	Submit project reports	E-mail or LMS Dropbox

in Table 1 (Weeks 3, 5, 20, and 30). Performance data for quantitative scales are shown in Table 2.

Teacher content and skill perceptions. A 29-item instrument assessed five perceptual constructs that have demonstrated influence on teacher transfer: *perceived value*, *utility*, *benefits*, *feasibility*, and *fit*. Sample items are as follows: value ("I see how the ideas I am learning during the RET program are valuable to me as a teacher"), utility ("I see how what I am learning here will be useful in teaching my students"), benefits ("I recognize the benefits of skills acquired during RET"), feasibility ("It seems feasible to use the skills and ideas acquired during RET to teach my students"), and fit ("What I learned during RET fits well with my own teaching"; α = .94–.97).

Teacher self-efficacy to transfer. Teachers' self-efficacy in transferring the engineering skills and principles to their classes was assessed (on a 5-item Likert-type scale). A sample item is "I am certain that I can efficiently integrate the ideas attained during RET in my classroom teaching" (α = .98).

Teacher use and integration of content. Teachers' intent to use (Weeks 3 and 5) and then actual reported transfer (Weeks 20 and 30) of the engineering content was measured on a 6-item Likert-type scale. A sample item is "I integrated the ideas attained during RET into my own teaching" (α = .96–.98).

Attribution of change. Midway through the on-site experience (Times 2–4), the perceptions questionnaire included teachers' attribution of change. Four items addressed teachers' attributions of their growth in teaching, such as using more engineering-related principles, to the RET experience. A sample item is "Because of RET, I implemented more engineering research into my classroom" (α = .88).

Table 2
Teacher Perceptions Subscale Scores Over Time

	Time 1	*Time 2*	*T2−T1 diff.*	*% change*	*Time 3*	*T3−T2 diff.*	*% change*	*Time 4*	*T4−T3 diff.*	*% change*
Value	5.76	5.97	+0.21	+3.65	5.86	−0.11	−1.82	5.93	+0.07	+1.19
Utility	5.61	5.85	+0.24	+4.28	5.93	+0.08	+1.38	5.85	−0.08	−1.41
Benefits	5.75	6.01	+0.26	+4.52	5.88	−0.14	−2.25	5.79	−0.08	−1.42
Use	5.74	6.25	+0.51	+8.89	5.53	−0.72	−11.56	5.35	−0.18	−3.27
Efficacy	5.60	6.19	+0.59	+10.54	5.35	−0.84	−13.57	5.31	−0.04	−0.75
Feasibility	5.58	6.15	+0.57	+10.22	5.17	−0.98	−15.98	5.36	+0.19	+3.75
Fit	5.39	6.04	+0.65	+12.06	5.67	−0.37	−6.18	5.67	0.00	0.00
Attribution of change	N/A	5.93	N/A	N/A	5.50	−0.43	−7.25	5.55	+0.05	+0.91

Note. All mean values are rounded to two decimal places, and percentages are rounded to whole numbers. Percentage change is calculated as percentage of the full range of the scale. Times 1 and 2 were during the on-site RET, and Times 3 and 4 were during at-school implementation.

Journals and discussions. Two different types of digital tools gathered teachers' and mentors' generative data in the LMS. Journals were private and unstructured, with entries by participants' choice in documenting their experience. They yielded 324 independent journal entries. Discussions were structured and interactive, with prompts to focus responses. Mentors' discussions were visible to other mentors, while teachers' discussions were visible to both peer teachers and mentors. Thirteen (13) discussion events (7 for teachers, 6 for mentors) each presented four to six, open-ended prompts. A sample question for teachers is "Which of the skills from the research mentoring experience are you most likely to integrate into your school classroom first, and why? How do you imagine including that skill set in your teaching?" and for mentors is "What do you feel that your teams of teachers are learning in the on-site research experience? What evidence do you see of this? Please provide evidence that you have observed." The 50 discussion questions/prompts for teachers generated 833 responses, and the 16 for mentors generated 44 responses.

Online implementation planning and discussion. Teachers discussed projects together online to support school-based transfer of engineering-related knowledge and skills for students. Eight prompts invited teachers to develop and share planning and reasoning about transfer and integration for their classrooms, and they openly discussed each other's project ideas in the secure online system.

Applied projects. Teachers proposed and implemented projects transferring engineering-related knowledge and skills to their classrooms and studying the process. Proposals included a lesson plan (what students would do) and a research plan (how teachers would study and evaluate students' activity and outcomes). Two mentors gave independent feedback on each proposal, and funding was provided to support implementation. After implementation, teachers wrote up reports on project outcomes, including evidence of student learning, development, and perceptual change.

Analysis

Mixed-method analysis and synthesis of data were based on the systemic framework, with attention to the nature and functions of dynamic social networks as appropriate to the outcomes of interest and nature of the data (Hardré et al., 2013; Mertens, 2010). In studying learning, systemic research analysis involves exposing, observing, and considering the integrated interactions among internal and external factors on human change and behavior (Hardré et al., 2014; Hardré et al., 2015). Quantitative data means were generated and then compared over time for patterns of development and change, along with magnitude and statistical tests for significance of change over time (Denzin & Lincoln, 2003). We utilized the paired-samples t-test to compare scores for the same participants on the same characteristics over multiple administrations of the assessments (Johnson & Christensen, 2014). Qualitative data were coded independently by multiple researchers, who then organized and condensed them into themes and compared those for patterns of meaning and change (Stake, 2010; Yin, 2011). Both types of results were then synthesized and triangulated to investigate the teachers' developmental processes (Johnson & Christensen, 2014; Mertens, 2010; Teddlie & Tashakkori, 2009). To achieve systemic convergence, a theme or observation needed to originate with at least two independent data sources and occur clearly in multiple instances. Data from various sources triangulated for each finding were blinded between sources and drawn from different data collection events (Fraenkel & Wallen, 2006; Stake, 2010; Yin, 2011).

Results

The results are presented in the following sections, structured by the five components of the hypothesized process of teacher professional learning and transfer (see earlier) and the corresponding five-part developmental process framework (Figure 1). Mixed-method evidence of all types and from all sources is integrated and synthesized. Where *verbatim* evidence is succinct enough to capture, brief illustrative quotations are provided.

Component 1: Teachers' Initial Profiles, Goals, and Expectations

Teachers come to professional development experiences with their own goals and interests, which influence what they attend to, engage in, and put forth effort to learn. We sought to understand what personal and professional goals and interests these teachers brought to the professional development experience. Key features of participants' initial profile characteristics (beyond simple demographics) provide context for data to help frame results and emergent findings. Assessment of teachers' perceived needs and alignment of their expectations with learning targets and developmental goals are important, because lack of alignment can thwart learning and development. Questions on the introductory questionnaire used for system training and orientation (Day 1, on-site) invited teachers to describe their "ideal day or class at school" and articulate what they "expect to learn at RET." The first question illuminated teachers' personal philosophies and current work constraints, and the second exposed their explicit expectations of, and goals for, their experience.

Ideal day. Responses included characteristics from affective to administrative, generally featuring four key characteristics. First was freedom from paperwork and other disruptions of focus on teaching (admitting that such disruptions are frequent and frustrating): "The day to go as planned, which rarely happens. Problems inevitably arise." Second was personal affect, such as confidence and competence to teach what students needed most to succeed (indicating that they often do not feel this way): "I would be fully confident and comfortable with the curriculum."

Third was quality of the content and lesson materials (recognizing that they often use materials they consider inadequate): "Having a creative and engaging lesson." Fourth was students' engagement and positive learning outcomes (indicating that in secondary classes in particular, students do not behave this way consistently): "My ideal class is one that asks questions and is fully engaged and curious. It is a great day if I see my students growing and learning."

Goals and expectations. Teachers' responses explicitly included reasons for what they expected to learn, framed as their personal and instructional goals, featuring the following themes. All expressed desires to "learn about engineering" or "understand engineering better": "I expect to learn about engineering and how to relate it to my classroom instruction." Predominant goals were for transfer to teaching, primarily articulated as integration into their current teaching. Many articulated local goals of engineering-related lesson planning and integration into existing instruction: "I want to be able to convert our research this summer into lesson plans for my students." Others articulated global goals of curriculum redesign and major innovation: "My class is important, so I want to create new, innovative curriculum for it."

These findings confirmed that teachers' overall expectations and goals were consistent with the program's conceptualization of the process through which RET could influence teachers' learning and development in engineering content and skills and, through their transfer, influence students' development and change.

Component 2: Teachers' Experience and Engagement

We sought to understand how these teachers' engagement and effort (individually and in community) influenced what they gained from the professional development, in knowledge and skill learning as well as in perceptual and conceptual change. Teacher participants' engagement was defined as their being invested in, and actively involved in, program activities and was operationalized to include four components: (a) behavioral—they voluntarily approach and persist in program tasks, initiate, and innovate, contributing more than minimum effort and achievement; (b) cognitive—they are attentive and focused on individual and group projects; (c) motivational (includes perceptual)—they exhibit motivationally positive characteristics and strive toward personally defined learning and development goals; and (d) social—they develop meaningful relationships with mentors and peers.

Multisource evidence for engagement (products, journals, discussions, mentor observations, and evaluations) demonstrated that teachers cognitively and behaviorally engaged in all on-site program activities, with goals focused primarily on enhancing their teaching through transfer. They were attentive and focused on tasks, approached, and persisted, even when faced with challenges. Participants were motivationally engaged, seeking out enrichment of their teaching skills beyond requirements, driven by desire to meet their students' needs. Teachers also engaged socially, clearly developing meaningful relationships with both engineering mentors and teacher peers, relationships that carried through the entire program year and beyond.

Teachers demonstrated excellent motivational and social engagement in both face-to-face and online discussions, questioning and supporting each other. Data in the LMS showed that teachers participated beyond minimal requirements, volunteering additional information and insights needed to achieve goals. They also regularly reached out and supported and helped each other. Mentor observations verified that the teachers were engaged cognitively and behaviorally, motivationally and socially. Some of these observations emphasized motivation for task success and effective social networking: "They are staying engaged and focused. . . . They are motivated and finish tasks fast and professionally. They have great discussions within the group and designate each of the members with subtasks to tackle." Others emphasized dedication to task completion:

> They are always at the bench when they are in the lab, or working on their data when in the office. They are very dedicated and engaged in this project. I never see them doing things unrelated to the project in the lab or office. Moreover, they will stay late if necessary to complete the day's activities.

Still other mentor observations underscored that teachers did not settle for minimal task completion but strove to produce excellent results, even when it required extra time and innovative strategies: "They sought out information online to fine-tune [the task] they are working on. They seek out individual meetings with officials [and other experts] to answer questions related to their research."

Mentors observed teachers as socially engaged, actively participating in groups; seeking help, advice, and expertise from each other; and developing and producing more collaboratively than individually. Teachers shared leadership and collective expertise: "They work together to figure out solutions to problems and how to do certain tasks. They treat each other with great respect and equity." They not only engaged with each other, as peers in research, but integrated into the engineering lab community and became a part of it: "Together they all utilize each other's strengths to forge ahead on collecting data and solving problems they encounter before coming to ask me questions. The teachers have blended right into our research group and are respected by [everyone there]."

Component 3: Teacher Learning and Development

We examined the data for elements of teachers' learning and development, including cognitive–perceptual (internal), motivational–behavioral (externally observable), and conceptual–behavioral (change-actionable) factors. Specific learning and change spanned engineering-related and research-related knowledge and skills, knowledge of engineering as a profession, perceptions of themselves as teachers of engineering (identity development), and recognition of the transfer potential of their engineering knowledge and skills. Perceptions promote engagement; engagement facilitates learning and development, and teacher learning forms the critical bridge to teacher transfer and student learning. Teachers' learning and development were assessed both as self-report and mentor report, and additional evidence came from discussion entries and applied project documents.

Engineering-related content and skills. Teachers' reports of what they were learning (during the on-site phase) and of what they had learned (reflectively after returning home) ranged from discipline-specific engineering skills and principles to more general skills of research, communication, and collaboration. One strong theme was the power and role of collaboration: "I learned engineering principles and how to work with others to create a product. This is teaching me to collaborate and accept others' ideas." A second strong theme was the effect of scholarly role-modeling: "Talking to researchers in a field and hearing them interact hones my own ability to ask questions." A third was the generalizable and transferable skills of research and design: "how to compile and gather data through survey questions" and "I learned how the research process goes in engineering." Some teachers identified even more global and generalizable principles of research that merged into philosophy of inquiry, juxtaposed with very specific technical knowledge:

> I have learned a lot about how to conduct research. I have learned that research is never "DONE" and should always leave you searching for answers to questions you discovered during your initial research process. I have learned more about fracking, culturing cells, telecommunication, fiber optics and patents.

Many of these lessons about engineering and scientific research came with direct applications for secondary teaching: "I am learning about narrowing one's focus during developing a research question. This will help me when I assign research to students."

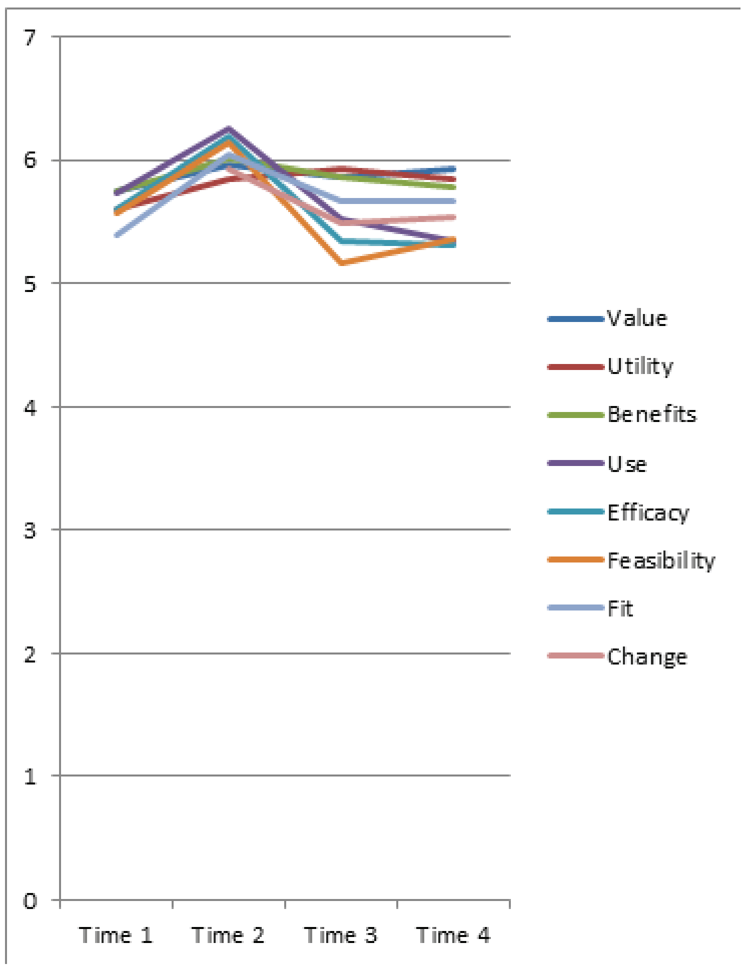
Engineering as a profession. Much of teachers' learning converged on better understanding of the field of engineering, with identifiable implications for bridging to their teaching. These included motivational strategies ("what hook to use to grab the attention of students that will give them an interest in engineering fields") as well as awareness of overlap with their existing instructional strategies ("I learned that it wasn't a far reach from what I was already doing in class to include engineering subject matter"). Some teachers reported epiphanies heralding long-term paradigm shifts: "Definitely learning new resources for creativity in my classroom. Absolutely learning about new techniques and networking. I feel like RET is opening a door for me that I didn't even know existed."

Mentors' independent observations of teachers' learning were consistent with teachers' self-reports (providing validity evidence). Mentors observed and identified evidence of teachers' learning and growth in areas from technical laboratory and engineering knowledge, skills, and tools to recognizing the value and benefits of more general teaching strategies like inquiry-based learning, collaboration, and innovation for interdisciplinary project development.

Perceptions. Given their influence on learning and development, it was important to assess teachers' perceptions. Table 2 shows the means of teachers' content and skill perceptions through the program. Variables include value, utility, benefits, use, self-efficacy, feasibility, fit, and attributions of change. Figure 2 is a line graph of trajectories illustrating patterns of change over time, and Tables 3 and 4 show the results of the statistical significance tests.

Even with the small sample size (N = 19), teachers' perceptions of the content

Figure 2
Teachers' perceptual trajectory of change over time. The figure presents group means on all perception questionnaire subscales over four administrations.



demonstrated statistically significant changes over time (at $p \leq .05$). The most significant changes occurred when teachers left the on-site experience, yielding patterns of perceptual change over time that are important to understand. Overall, perceptions began strong and increased dramatically while on-site (3.65%–12.06%). They demonstrated mixed change (both positive and negative) after leaving the on-site experience. Notably, the engineering content and skill perceptions (value, utility, and benefits) that were not explicitly linked to ability to transfer remained high or dropped less off-site (+1.38% to −2.56%). However, as in past studies, perceptions explicitly linked to transferring the engineering content and skills to their classroom (use, feasibility, fit) dropped more significantly (−6.18% to −11.56%), and self-efficacy dropped sharply (−13.56%). General perceptions all remained high and relatively stable over time, while explicitly transfer-relevant perceptions

Table 3
Effect Sizes and Observed Power for Change Over Time

	F-statistic	*p-value*	*Effect size*	*Power*
Value	F(3,44) = 0.099	0.960	0.007	0.067
Utility	F(3,44) = 0.181	0.909	0.012	0.081
Benefits	F(3,44) = 0.132	0.940	0.009	0.072
Use	F(3,44) = 1.289	0.290	0.081	0.320
Efficacy	F(3,44) = 1.420	0.250	0.088	0.350
Feasibility	F(3,44) = 1.492	0.230	0.092	0.367
Fit	F(3,44) = 0.556	0.647	0.037	0.155
Attribution of change[a]	F(2,33) = 0.538	0.589	0.032	0.131

Note. Effect size and power statistics are computed using Wilks's lambda, effect as partial eta squared. Significance target of difference between means is $p < .05$.
[a]Data analysis only available for Times 2–4.

Table 4
Mean Trajectory Significance Tests of Change

	Significance of incremental change scores (p-value)			*Significance of nonincremental change scores (p-value)*		
	Times 1–2	*Times 2–3*	*Times 3–4*	*Times 1–3*	*Times 2–4*	*Times 1–4*
Use	.07	.04*	.19	.68	.00**	.40
Efficacy	.28	.01**	.79	.42	.00**	.51
Feasibility	.12	.01**	.49	.50	.02*	.69
Fit	.09	.05*	1.0	.55	.06	.52
Attribution of change	N/A	.27	.88	N/A	.17	N/A

Note. N/A = not applicable, as this subscale was not administered at Time 1; because it is an attribution of change, no initial assessment was possible.
*$p < .05$. **$p < .01$ for mean significance of change (2-tailed).

varied more dramatically from on-site to off-site but recovered and stabilized near their original levels (from baseline to Time 4). Overall, teachers' motivationally relevant perceptions remained high and positive throughout the program.

In the qualitative data, teachers articulated similarly positive perceptions consistent with their self-reporting on the questionnaires and with mentors' independent reporting. Together these data present consistent, independent, multisource evidence of these same patterns in perceptions and of their correspondence with learning and developmental outcomes, such as links between engineering skills and secondary math and science, the appropriateness of engineering-related activities for secondary classes, and confidence in designing engineering lessons for secondary classes. The qualitative data also verify important perceptual changes not explicitly addressed in the quantitative measures, such as shifts in understanding of student access to engineering careers and intent to shift focus of instruction regarding engineering careers.

Teachers reported changes in their overall confidence with research and the positive impact of those changes on their self-efficacy for teaching it: "I felt much more confident with the [research] process. I felt better prepared to teach." They identified perceptual changes regarding engineering and engineering-related careers that altered how they would teach and how they would advise students regarding careers: "As a result of this program, I am more confident having students engage in the engineering process. With an understanding of the types of questions engineers try to answer, I feel confident designing lessons that incorporate engineering skills."

Math teachers, particularly, experienced change in their perceptions of engineering, including its nature, difficulty, and—most profoundly—accessibility for their students: "My perception of the difficulty level [of engineering] changed. Before RET, I assumed I would not be able to incorporate any engineering research into my math classes." They reported perceptual shifts that enabled integrating engineering-related instructional strategies across math courses at all levels: "My self-perceptions related to science and math changed to where I would be able to integrate engineering lessons from basic, intermediate algebra and geometry, to more advanced trig/precalc and [Advanced Placement] statistics levels."

Their reported shifts captured intersections between knowledge of engineering skills and the profession, the role of math within engineering, and students' aptitudes and interests:

> My perceptions of who would make a good engineer have changed. . . . This will change how I talk to students about becoming an engineer. . . . I will try to place more emphasis on what engineers accomplish. If students are inspired to solve relevant problems, then even some students that are not gifted at math will want to pursue engineering.

Transfer planning. Data from the planning, discussion, and project documents showed that the teachers applied a large range of skills and expertise that they had learned at RET in their projects. These included both engineering-specific and general knowledge and skills: research process and organization, assessment and measurement, engineering concepts, formative and summative feedback, research design and hypothesis testing, inquiry-based learning strategies, and so on. This direct application of knowledge and skills that they admitted not having before RET is excellent evidence that they learned these skills effectively in the program. Beyond their own plans, the teachers' comments on each other's project plans demonstrated engineering-related reasoning and skills.

The teachers' project proposal scores (given independently by two different mentors) were moderate to high, indicating good quality of research project planning and engineering skill integration. Teachers created developmentally appropriate and intellectually challenging projects for their students, featuring inquiry-based learning with formative feedback. They also promoted students' understanding of engineering careers. Project documents and discussion boards provided ample independent evidence that teachers had learned and developed as they claimed and were preparing to translate that learning into innovative, appropriate engineering-based learning experiences for their students.

Component 4: Teacher Transfer, Implementation, and Integration

Teachers' learning and development influence their transfer of knowledge and skills from professional development as evident in their change of practice. Therefore we investigated how these teachers' learning and development influenced their transfer of knowledge and skills from professional development, as evident in their change of practice. The RET experience supported participating teachers in their efforts to translate their own learning into authentic, inquiry-based curricula for their own classes and students. This goal of transfer, implementation, and integration was not merely creating an engineering-related lesson but systematically integrating principles and strategies of engineering research and inquiry-based learning into their instruction and assessment.

Evidence for these goals from multiple data sources (journals, discussions, e-mails, mentor observations and evaluations, and classroom projects) demonstrated that the teachers (a) worked to integrate what they had learned, both of inquiry-based instruction and of engineering principles and concepts; (b) made linkages between engineering knowledge and skills and their math/science subject areas, and between their laboratory learning environment and their students' classroom learning environments; and (c) strove for authenticity, even if their implementation was challenging or felt limited by transfer across environments.

Teachers' transfer and integration projects. Mentors' observations encompass what they saw teachers preparing for their classrooms during RET and how they saw those preparations develop: "The teachers were not sure about lesson plans to bring back to classrooms during the first pedagogy workshop in Week 2, but they have developed great lesson plans for their [project] proposals." They underscored the change from traditional worksheets and simplistic, menu-driven lab activities to authentic, inquiry-based activities:

> The summer research experiences of my teachers are helping them to expand their proposed hands-on classroom activities to include and involve more real-world-type experiences rather than contrived, cookbook activities. The summer research experience has reinforced the idea of what much more powerful real-world experiences are, even if they may not perfectly work out the first time, compared to safe and predictable labs.

For nearly every participant, mentors observed substantive change in understanding that led to plans to transfer, borne out in both discussions and their applied project proposals:

> We've spent time working on technical details of what exactly students could do in authentic, guided-inquiry labs that relate to corrosion materials, in particular minerals, that lead to the formation of soils. I know these efforts were successful because many of the discussion topics have been incorporated into their [transfer projects].

Evidence for what teachers actually transferred (from journals, discussions, and project reports) demonstrated that teachers transferred what they planned and, in addition, integrated discipline-specific engineering skills, principles, tools, and strategies, along with more general skills of laboratory research, communication, and team collaboration.

Engineering specific. Some teachers reported transferring engineering-specific technical skills to their classes using tools introduced in their immersion experiences: "My students built an aquaponics system." One featured area of application for engineering was weather, and several of the teachers built on those ideas. "Severe storms and National Weather Center websites integrated into lessons this year." Others used more global engineering skills, such as the engineering design process they had learned:

> I was able to have the students follow the steps of the engineering design process to set up a presentation on Newton's laws. Including the engineering process helped make the students' projects much better . . . allowed me to cover the material in a more interactive way.

Still other teachers focused on more general skills from RET, such as organization, management, and collaboration: "I [am teaching] that it is important to know what section of the community you are trying to help before starting a project. I try to teach students how to work with others when trying to complete tasks, and to be open to differing viewpoints." Some teachers transferred ideas from guest speakers, along with basic engineering concepts, across multiple courses:

> I applied what I learned from the meteorologists. My Trigonometry students used the concepts of vectors by applying wind velocity data and plotting them on a hodograph. . . . The students in Intermediate Algebra became familiar with

> [bridge design software] and also built and tested various model bridge trusses made from balsa wood and hot glue.

Increased authenticity and interactivity. Nearly every teacher in the program reported global changes in the way they designed and implemented assignments in their classes as a result of their RET experience, from recrafting lab experiments to be more authentic in process to reframing research questions as more applied than esoteric and abstract:

> As a result of this program, I have students design and test their ideas for solving problems. In the past, we looked at purely scientific questions (what factors affect diffusion?) and data collection. Now I try to have students look at problems that are more relevant (how can we use our knowledge of diffusion to engage in tissue engineering?).

Communication and collaboration. Teachers reported making substantive changes in their communication and classroom practices, directly attributing these new teaching methods and practices to RET. Several teachers began using collaboration: "I am currently implementing [collaboration] in my classroom." Others transferred lessons learned on writing tests and assignments better and more clearly: "I am trying to more carefully phrase assignments to the class, after we talked so much about how questions in a survey could be misinterpreted." Beyond the "lessons" of RET, teachers attributed change in their teaching practice to the connections and community from RET: "Time spent with my peers and the many other professionals that I was able to meet with because of the RET program helped me to develop new lessons and methods of teaching that I am currently implementing in my classroom."

Many teachers also made explicit efforts to educate and inspire their students toward engineering careers by sharing their own experiences and by bringing program connections to their students through visits with university engineering mentors and students (both at their schools and on field trips to the university).

Component 5: Student Learning, Development, and Perceptual Change

The fifth and final component of the study's conceptual and functional model is student learning. The ultimate goal of any teacher professional development effort is impact on students. For this reason, we strove to identify what effects of teachers' transfer were evident in observable changes in students' perceptions, achievement, and aspirations. This teacher-reported data are in part informal observation of students and in part systematically collected data resulting from their applied projects. The following section reports teachers' observed evidence and self-reported indicators of their students' learning, development, and change that they attribute directly to their own integration and transfer of learning.

After implementing and integrating engineering-based methods, tools, and strategies, teachers reported directly observed and perceived improvements in student learning compared to previous methods of instruction. In addition to improved performance on tests and tasks, they reported enhanced engagement and enjoyment of science and math as well as recognition of the nature of engineering and engineering-related career awareness and aspirations. Several teachers who integrated the inquiry-based and project-based methods broadly attributed overall improvement in students' motivation and attitudes to those instructional shifts: "Many of my students enjoyed the project and reported being more engaged. They also felt a sense of ownership in testing their designs."

Content knowledge and skill gains. Teachers reported that their students' science test scores and transferable skills improved, traceable to the engineering lessons: "Students scored well on quizzes and tests on force, and are again applying the engineering design process to the end-of-year project"; "they gained better understanding of static equilibrium from making the bridges with the force sensors. They enjoyed the hands-on application and they had a better understanding of force in two dimensions." They observed that these skill gains were linked to the use of concrete applications (of otherwise abstract concepts) in authentic projects linked to a specific career field: "The Trigonometry students were able to connect the abstract concept of a vector to a real-life context. The Algebra students increased their knowledge of basic structural engineering terminology and responsibility."

Confidence and attitude. Beyond content skills, the teachers observed improved attitude and confidence in math and science classes, which they attributed to the engineering content: "Students have covered more material in more depth, and with a more willing attitude this year"; "my students have become more confident in their skills in fields of science and math."

Understanding of and comfort with engineering. Furthermore, teachers found students more informed and also more inquisitive about engineering as a career specifically, changes they saw only after introducing what they had learned in RET. One aspect of this developmental change was improved understanding of the engineering profession: "Some students in the class had directly asked about what engineering was like, and they told me that doing the project helped them see that engineering was about working in teams to solve problems." Another aspect was recognizing components of how engineers engage in research and problem solving: "My students have a better understanding of the types of questions engineers answer and the type of work they do. My students also have an increased interest in the work of biological engineers and the implications their work has for the future." Related to understanding the engineering profession and engineers' problem-solving processes was students' personally developing skills used by engineers: "They have better understanding of the field of engineering. They also learned how to gather information and data, and represent that data in a graphic. My students also learned how to work together and glean ideas from their peers."

Perceived access to and aspirations for engineering. As students learned engineering skills, old perceptions and barriers were reduced: "They are not as intimidated by engineering in general. Most of them feel capable in understanding the terminology and appreciated the application of some abstract math." Thus an outgrowth of understanding engineering and learning engineering skills was increased perception of students' own access to engineering as a professional goal: "I think more of my students, especially the females, now believe that the field of engineering is one that is available to them and they can be successful at it." Some students explicitly formed aspirations to become engineers as a direct result of their teachers' RET transfer and integration into their secondary courses: "At least one of my students has decided to major in industrial engineering."

Limitations

One limitation of the present study design was the absence of direct assessment of student outcomes, with dependence on teachers for observational and summary data as evidence of student learning and development. Including systematic researcher collection of student outcome evidence will strengthen future iterations of this research. The small sample might be seen as a limitation, but it allowed for rich, multimethod, extended data collection and deep analysis rather than relying only on superficial (largely quantitative) data, which has been characteristic of some past large-group studies of teacher professional development.

Discussion

The U.S. government and educational agencies are calling for secondary teachers to guide students into engineering careers without equipping them to do so. This research contributes to the field of teacher professional development by collecting and examining data that demonstrate the key components of equipping and supporting teachers to understand the authentic nature, value, and utility of engineering and then to translate that understanding into educational activities for their students. Studies of this kind address multiple challenges in the field of education, from how to help teachers educate and motivate students to consider careers in engineering to how to track the interactions of K–12 teachers with university mentors and measure the various impacts of their professional development and collaboration.

Authenticity in professional development is a double-edged sword. On one hand, we would like both research and professional development clear and neat enough to replicate. On the other hand, we recognize that an authentic experience cannot be predesigned and aligned to uniformity, or by definition, it becomes inauthentic. Authentic professional experiences are organic and fluid, and when they include a range of different disciplines or subspecialties, as this one did, they diverge even more. Matching the research data collection and analysis with this kind of developmental experience is tremendously challenging and requires an adaptive approach that recognizes the importance of emergent issues and captures indicators of change that may not have been anticipated from the start. At the same time, enough consistency in design, assessment, and methods is necessary so that these studies contribute meaningfully to what we know and also set precedent and foundations for what we still need to know. Educational researchers need to generate adaptive research in authentic learning spaces to advance our methods into the next generation.

This study design with extended data collection enabled researchers to identify the trajectory of change among participating teachers and further illuminated pathways to learning and perceptual change for students through their teachers' transfer of program content and methods. The five phases/components are linked through continuous systematic, multisource, multimethod data collection. The strength of the findings is in the consistent results from independent and blinded sources, both synchronous and asynchronous.

Much of the most profound change evident in this project data was not taught directly in a lesson or lecture but developed "in the trenches" at RET and afterward, as teachers sought to translate and transfer what they had learned, with support from their community of mentors and peers. The change occurred generatively and organically, as part of the dynamic process of immersion and struggle, cognitive and perceptual awareness, recognition and change, growth and development, maturation and dissemination. This is the process depicted in the study's conceptual process (Figure 1). Though the process is modeled in a (simple) linear way, the authentic experience is systemic and complex.

The five components are integrally connected: teachers' goals and expectations, their consequent engagement in the professional development experience, their learning and development, and subsequent transfer to classrooms, from which their students also learn and develop. As mentors and peers together supported the teachers' productive self and content perceptions, and aligned the experience (including structural supports) with their needs and expectations, teachers achieved their goals and fulfilled expectations—and most exceeded them. Through the interactions of valued content, relevant and challenging activities, respected role models, and interpersonal and community support, teachers sustained motivation to follow through with implementation planning at home. With the additional resources of supply grants and school administrator support, teachers succeeded in transfer projects that included not only content but also the energy and passion of their experience, promoting students' math and science learning, development of understanding about engineering, and interest in engineering careers.

Alignment of learners' goals and expectations with the design of learning environments and experiences promotes motivationally positive self and content perceptions and consequent task engagement. Motivation-related perceptions predict probable utilization and openness to work at implementing and support acculturating to new content and contexts. This same power of perceptions has been demonstrated for teachers at various levels of education (Hardré & Chen, 2006; Hardré et al., 2013; Hardré et al., 2015). Motivationally positive perceptions are productive, as they support and predict desired behaviors, such as deep and adaptive learning, transfer, and authentic utilization of knowledge and skills, for teachers and, consequently, for their students.

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