

## Network analysis of qualitative results from a national survey: Impact of outreach on physics student development

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Student experiences in physics beyond the classroom and their role in supporting student development have been the subject of increasing research attention in recent years. Results, typically from small studies at single institutions, have illustrated that facilitating informal physics experiences for nonscientists can enhance student disciplinary identity, learning, sense of belonging, and career skills. However, it is essential to examine whether these impacts are the sole provenance of institutions with well-developed outreach programs or if they may be shared by institutions anywhere. This work reports on the analysis and findings of responses to three open-ended questions presented to students who indicated they had engaged in facilitating outreach programs as part of a national survey distributed through the Society of Physics Students network in spring 2023. Employing a network analysis with Girvan-Newman clusters revealed six core themes of student experiences: *community participation*, *resilience*, *transformation*, *audience dialogue*, *disciplinary development*, and *disciplinary connectedness*. The first four of these clusters were observed to be highly interconnected, providing evidence that the impacts and experiences within them are interrelated with other clusters, particularly interactions with the audience, which is a central feature of informal physics programs. In particular, student experiences highlighted that facilitating informal physics programs enhanced their resilience and belonging, grew their physics identity, provided opportunities to develop essential career skills, and cultivated a growth mindset.

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### I. INTRODUCTION

Physics departments across the country aim to enrich the educational experience of physics majors and prepare them for their careers. While high-quality coursework and lab activities are central priorities, students often benefit from impactful experiences beyond the classroom. One such experience is engaging students in extracurricular activities such as physics outreach, also called public engagement or informal physics programs, that university students facilitate. These programs can differ significantly in size and frequency [1,2], but they give physics majors opportunities to share their enthusiasm for physics and astronomy with

the public, helping them see themselves as active members of the physics community [3–15].

Less structured than coursework, outreach programs offer physics majors opportunities beyond the traditional focus of physics coursework, such as leadership, creativity, teamwork, and communication. According to studies by the American Physical Society and the American Association of Physics Teachers, these skills have been identified as a high priority for physics programs to prepare students for careers in the 21st century [16–20]. In fact, communication remains regarded as one of the main skills that contributes to the employability of students in science, technology, engineering, and mathematics (STEM) [16,21–23]. A recent survey from the American Institute of Physics's Statistical Research group shows that more than 80% of physics bachelor's degree holders who graduated in 2019 or 2020 report that they work as a member of a team daily in their job [24].

By bringing physics beyond the classroom, students are expected to engage with material in different ways and

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gain opportunities to interact with a variety of personnel from their home departments. One of the major facets of these programs is students engaging in self-explanation of physics concepts [4,10,12,25–27], which has been noted to enhance their learning [8,9]. Students also gain the opportunity to work side by side with graduate students, researchers, and professors to create and facilitate public engagement, which may help them build professional networks and identity. Serving as ambassadors for physics helps them stay motivated and interested in their major. They get recognition as STEM professionals by the general public, their professors, and their peers [9,11–13,15,28–30].

These often impactful and transformative experiences in communicating physics to diverse populations allow students to gain new perspectives and develop self-recognition as physics professionals. By explaining physics to others, students can improve their conceptual understanding. In other words, facilitating physics outreach programs helps students build a disciplinary identity and a sense of belonging within their major and the physics community—factors found to be impactful for student retention and success in the field [31–36].

In our pilot study at Texas A&M University, we surveyed and interviewed students who facilitated five physics outreach programs, ranging from short student-created demonstration videos to a large-scale physics festival attended by thousands [12]. The data in this prior work included 117 survey responses and 35 semistructured interviews, representing both undergraduate and graduate students. The results were inspiring: students who participated in physics outreach reported growth in their physics identity, a stronger sense of belonging within the physics community, and the development of essential 21st-century career skills. Specifically, they reported improvements in communication, teamwork, networking, and design skills [9,11–13].

However, our results, as well as other available research, were limited to individual departments and a small number of engaged physics majors [6,7,9–13,25–27,29]. Addressing this gap by surveying a larger number of students engaged in outreach from diverse types of institutions is important. If the Physics Education Research community has compelling data showing that engaging physics majors in facilitating outreach programs can help them build their disciplinary identity and sense of belonging within the physics community, while also enhancing their career readiness by fostering teamwork, communication, and design skills—this could be of significant interest to many physics departments. These benefits, which enhance students' university experience by involving them in outreach facilitation, can be achieved by physics departments of any size without requiring significant financial investment or major curriculum changes. In this paper, we present the results from the qualitative analysis of our first nationwide survey.

Building on our pilot study survey [12] and leveraging collaborative expertise from Texas Lutheran University, Texas A&M University, the University of Texas at Austin, and the Statistical Research Group of the American Institute of Physics, we developed a new survey instrument incorporating both closed- and open-ended questions [28]. To maximize responses from undergraduate physics students, we distributed the survey to approximately 5500 individual physics majors through the network of Society of Physics Students (SPS) chapters. This network is primarily composed of chapters at U.S. institutions with a small number of chapters in Canada and Mexico. This effort resulted in a robust dataset of 704 responses, allowing for a more comprehensive analysis of how outreach programs support undergraduate students than previously available.

The survey aimed to evaluate students' perceptions of their physics identity, sense of belonging, mindset, and career skill readiness, while also collecting data on their engagement with physics outreach programs and demographic background. In our previous work, we described the survey design, administration, and regression analyses of the closed-ended items [28]. That quantitative analysis demonstrated statistically significant associations between student outreach facilitation and their mindset or sense of belonging; however, it did not capture students' lived experiences or examine relationships among constructs beyond pairwise comparisons. In the present study, we analyze the open-ended survey responses, in which students articulated concise yet substantive reflections on their experiences facilitating informal physics programs. Drawing on our largest dataset to date, we employ a mixed-methods approach to identify central themes and to examine the structure of relationships among constructs including students' physics identity, sense of belonging, mindset, and career-related skills across a national sample.

## II. METHODS

To study the impact of student facilitation of informal physics outreach programs, we created a new survey. Drawing on our prior studies at a single institution [8,9,11–13], the survey combined closed, Likert-scale questions and a small number of open-ended questions intended to sample respondents' perceptions of their physics identity, sense of belonging, self-efficacy, and career skill development. A more detailed description of the survey may be found in Perry *et al.* [28]. In short, the survey was designed and validated through a pilot distribution to three collaborating institutions, then reviewed for quality [28]. The survey was then distributed to approximately 5500 students through the SPS network.

Respondents who indicated they had participated in informal physics outreach programs received the following prompts. Each such respondent received all three questions and could answer all or none of them. The prompts were:

- What has been your most memorable experience from participating in physics/astronomy outreach?
- How has participating in outreach provided you with opportunities to utilize your physics/astronomy knowledge in a real-world setting?
- How has your perception of yourself as a physicist changed through your participation in physics/astronomy outreach?

### A. Framework

Analysis of responses to the open-ended questions employed a deductive coding scheme based on theories which had been present during our prior studies [12,13]. Throughout our prior studies, student responses revealed that engagement in informal physics outreach programs had multifaceted impacts, encompassing academic, personal, and professional dimensions. Student responses rarely focused on a single construct or idea, often rapidly or simultaneously touching on experiences or ideas related to identity, community, and skill development. As such, no single theoretical framework was complete enough to capture the complexity of their experiences. Aligning with learning sciences [37] and to reflect the individual, social, and evolving aspects of students' experiences during informal programs, we drew upon multiple learning theories. The theories which guided this work included situated learning theory for conceptualizing the learning processes [38], transformative learning theory to define how powerful learning occurs [39,40], and models such as Hazari *et al.*'s framework [41] and the Dynamic Systems Model of Role Identity [42] to articulate the construct of identity. In total, 49 codes were used in this work, organized into the following seven categories: *identity*, *community*, *affect and experience*, *disciplinary skills*, *nondisciplinary skills*, *mindset*, and *outcomes*. These categories, employed in our prior studies, were used to capture the experiences of students who facilitated informal physics outreach programs. In particular, they described impacts on disciplinary identity; interactions and a sense of accountability with the broader community; transformational experiences related to student affect and experience; and the development of career skills identified as essential for 21st-century physics careers [12,16]. Additionally, these theories addressed students' mindsets toward physics [13], as well as their career aspirations and impacts on their physics learning [9].

The category of *identity* drew from three complementary theories. The first is defined by Hazari *et al.*'s model of physics identity [41] incorporating interest and motivation, performance and competence beliefs, recognition, and sense of belonging. The second model, the Dynamic Systems Model of Role Identity (DSMRI), conceptualizes identity as a complex dynamic system that is situated within specific roles and contexts [42]. The DSMRI comprises four interrelated components from which role

identity is emergent. These components include ontological and epistemological beliefs about the domain, purpose and goals related to the role, self-perceptions and self-definitions within the role, and perceived action possibilities available to the individual. These are not static traits but mutually constitutive elements that dynamically change through engagement in role-relevant activities. In the context of this study, the DSMRI informed codes capturing how students' self-perceptions as physicists, their beliefs about what physics entails, and their sense of what actions are available to them may have shifted through their engagement in informal physics programs. Third, following Rethman *et al.* [12], we incorporated situated learning theory which defines learning as becoming part of a community, or "becoming," through social interaction and engagement in its practices [38,43]. Those new to a field, novices, move toward more expert status via legitimate peripheral participation and the adoption of norms and practices consistent with the community [44]. Based on this operationalization, we coded for legitimate peripheral participation. Situated learning theory has informed studies with similar aims to the present work. Fracchiolla *et al.* [6] used a community of practice framework to examine identity development in two graduate physics students involved in outreach. Likewise, Prefontaine *et al.* [29] analyzed interviews from students in three outreach programs to explore how participation shaped their professional identities.

Categories of *disciplinary skills* and *nondisciplinary skills* were also based on operationalization of situated learning theory, specifically highlighting the practices and skills common to physicists. The category of *disciplinary skills* had codes for technical physics or mathematical skills, conceptual understanding of physics principles, developing a sense of real-world connections, and engaging in design.

Drawing on recommendations of skills defined as essential for 21st century physics careers [16], the category of *nondisciplinary skills* included creativity and innovation, teamwork, leadership, networking, and communication with peers or audiences. Communication was further nuanced through two subcodes, scaffolding and zone of proximal development, which were also commonly observed in our prior work focused on learning [8,9]. These subcodes capture guiding others, here in physics, beyond their independent abilities [45].

The category of *community* incorporated codes of sense of belonging (also from Hazari *et al.*'s work [41]), connections with peers and audience, accountability at four levels (to the general public, to the scientific community, to outreach leadership, or role based), and impacts from authentic interactions with audience members. Codes related to connections and accountability also stem from situated learning theory where novices adopt the norms and practices of the community into which they are "becoming" [44].

The category of *affect and experience* drew primarily from transformative learning theory which emphasizes the

importance of critical reflection by the learner, which can lead to a fundamental shift in their frame of reference, perspective, worldview, beliefs, or assumptions [39,40,46]. For learning to be considered transformative, it must significantly alter how the learner interprets or understands the world, such that their previous ways of thinking are no longer sufficient. Drawing on this theory, we included codes for seeing new perspectives, transformational experience, changing assumptions, excitement in facilitators or audience, being uplifted and empowered, desire to persist in the field or major, feelings of authentic purpose or impact from engaging in outreach programs.

The category of *mindset* was divided into two parts: growth and fixed [47]. Each mindset category was further subdivided into three categories of outreach to discipline, discipline to outreach, or ambiguous. These codes indicated whether students attributed their fixed or growth mindset to their experiences in outreach and carried them back to their disciplinary coursework, whether the reverse happened, or if the relationship was ambiguous. As the primary goal of this work was to determine the impact of student facilitation of informal physics outreach programs on student development, it was essential to distinguish whether the observed mindset impacts stemmed from participation in outreach activities or from engagement with the formal curriculum. In nuancing mindsets with the three subcodes, we were motivated by results from the quantitative analysis of survey responses which showed a statistically significant link between student participation in outreach and possessing a growth mindset [28].

The final category of *outcomes* incorporated codes based on respondents' trajectories toward an academic, a non-academic, or a teaching path. For all categories, only responses which were clearly related to experiences from facilitating or working with informal physics outreach programs were coded. Responses for other activities (e.g., summer research or coursework) were not coded in this work.

## B. Analysis

Coding of responses was conducted by five researchers. These five researchers consisted of two university faculty with a combined experience of 30 years in creating, running, and supporting a wide range of outreach programs, as well as one graduate and two undergraduate researchers who have been active participants in informal physics programs. To ensure consistent coding, surveys were divided into subsets of 10–20, which were coded by at least three of the researchers who then met to review codes applied, resolve differences, and refine definitions used. Then all responses were coded. At the end of this process, interrater reliability was  $\kappa \geq 0.90$ . Work from all researchers was then combined into a single file for analysis.

To explore the interconnectedness between the codes (ideas) defined above, we employed network analysis

followed by the use of a clustering algorithm. Network analysis is a valuable tool for investigating complex relationships between ideas, which comprise the fundamental units of qualitative datasets (e.g., categories, people, ideas, codes) [48–50]. This approach is akin to network analysis techniques employed in prior physics education studies [51] and is informed by methodologies used in our prior works [9,11–13]. Network analysis focuses on uncovering intricate relationships among fundamental units, which may include ideas or experiences [49]. These units can be expressed through various textual forms such as words, phrases, or sentences. For this study, we treated responses to individual open-ended questions as the primary semantic unit, as they represent the reasonable unit of responses capable of conveying distinct coded ideas. A sample of coded text from the study is shown in Supplemental Material [52].

Starting with the set of coded surveys, a co-occurrence matrix was produced including Pearson's correlation coefficients calculated using MaxQDA Analytics Pro. The co-occurrence matrix examines pairs of codes for both where they do and do not appear together in the text of documents within the dataset. To limit this work to the most significant relationships between codes, we examined correlations only with a significance level of  $p < 0.001$ . The matrix of correlational data is then used as input to create a 1-mode network using a separate software package, UCINET [53,54]. Within this software, the centrality of each code is calculated by assessing its proximity, measured in steps or distance along connecting edges (line between nodes), to all other codes. This process yields eigenvector centrality scores [55], which reflect the influence of each code within the network. To visualize these relationships, we used NetDraw, a tool that maps each code based on its direct and indirect associations. Direct ties (shown as a connecting edge or line between two nodes) represent statistically significant correlations between codes (represented as nodes), while mediated ties capture indirect connections, instances where a code is not directly correlated with another, but both share significant links with a third code [56]. For example, if code A is significantly correlated with code B, and code B is significantly correlated with code C, but code A and code C are not directly correlated, then code A is considered to have a mediated connection to code C. The network map presented later in this paper reflects the outcome of this analysis. In the visualization, node size and the number of connecting lines indicate the centrality of each code within the network [54,55].

The Girvan-Newman algorithm operates by iteratively identifying and removing the edges (connecting lines) with the highest betweenness centrality, where betweenness centrality quantifies the number of shortest paths between all pairs of nodes that pass through a given edge. By removing these high-betweenness edges, the algorithm progressively separates the network into increasingly

distinct communities of nodes that are more densely connected to one another than to nodes outside their group. At each stage of edge removal, the algorithm evaluates the resulting partition using a modularity score,  $Q$ , which measures the degree to which the observed community structure differs from what would be expected in a random network with the same degree distribution [57]. Higher values of  $Q$  indicate stronger community structure, and the partition that maximizes  $Q$  represents the optimal clustering solution.  $Q$  values above 0.30 are considered indicative of robust community structure [58].

In employing network analysis above other analytical methods, such as thematic analysis, we were motivated by the complexity of the codebook employed, as well as the need to have a method which could better address the complexity of interrelationships among ideas. Network analysis enables explicit examination of relational structure among constructs, rather than treating them as analytically independent [51,59]. Thematic analysis, by contrast, identifies and summarizes recurring patterns [60,61], but it is less well suited to representing the interdependencies, overlaps, and co-occurrences that often characterize complex qualitative data. Network analysis models codes as nodes and their co-usage or conceptual connections as edges, making it possible to visualize and quantify structural properties such as centrality, clusters, and bridges between themes. This relational perspective helps researchers identify influential or integrative codes, uncover hidden structure within the codebook, and better understand how meanings are constructed through interactions among concepts. As a result, network analysis supports more nuanced interpretation, reduces oversimplification, and scales more effectively as the number of codes and their interconnections increase. Network analysis is not merely an added layer of sophistication; it is methodologically necessary to align analytic techniques with theoretical claims about the interconnected nature of student development in informal physics environments.

### III. RESULTS

In this section, we describe our findings from a network analysis of coded responses to the three open-ended questions included as part of the survey. Of the 704 respondents to the survey, approximately 70% participated in some form of outreach. Of those, 239 responded to one or more of the three open-ended questions, yielding 621 nontrivial responses. Responses varied in length from a few words to lengthy paragraphs, with a majority of responses containing 2–4 sentences. The demographic information of the respondents is shown in Table I. Overall, the respondent pool reflected demographics across undergraduate physics when compared to data collected by AIP [24]. Results of the network analysis, at the  $p < 0.001$  level, are shown in Fig. 1. Results from the Girvan-Newman clustering

TABLE I. Demographics of students who responded to at least one open-ended question in the national survey. In some cases, percentages do not add to 100% as respondents could select “I prefer not to respond” or a similar nonidentifying answer. For ethnicity, respondents were allowed to choose multiple answers and categories have been condensed to two to preserve anonymity during the analysis phase.

| Demographics                         | Percent |
|--------------------------------------|---------|
| <i>Gender</i>                        |         |
| Men                                  | 49%     |
| Women                                | 41%     |
| Another identity                     | 7%      |
| <i>Institution type</i>              |         |
| Bachelor’s                           | 37%     |
| Master’s                             | 4%      |
| Ph.D.                                | 46%     |
| <i>Race or ethnicity</i>             |         |
| White                                | 62%     |
| Person of color                      | 27%     |
| <i>LGBTQIA+</i>                      |         |
| Yes                                  | 25%     |
| No                                   | 63%     |
| <i>International student</i>         |         |
| Yes                                  | 8%      |
| No                                   | 90%     |
| <i>Physical or mental disability</i> |         |
| Yes                                  | 47%     |
| No                                   | 48%     |

algorithm show six distinct clusters, distinguished by color and shape, with  $Q = 0.476$ . The research team assigned a name to each cluster which represents the common emergent theme of the interrelated ideas. Below, we describe and summarize each of these clusters, with representative supporting quotes and analysis from the survey responses. All quotes are shared verbatim unless indicated with square brackets to denote minor word changes to fit the sentence structure.

#### A. Clusters

##### 1. Green hourglass cluster: Resilience

The cluster represented by the green hourglass icons contained the codes: belonging, confidence in choice of major, empowering, and internal recognition. Experiences which related to these codes were observed to heavily favor internal shifts in students’ perceptions of themselves within the departmental community and how certain they were that they had picked the right major or area of study for themselves. The emergent role of outreach was seen in providing opportunities for students to reflect on their own abilities and learning, as well as their social connectedness and integration within the physics community.

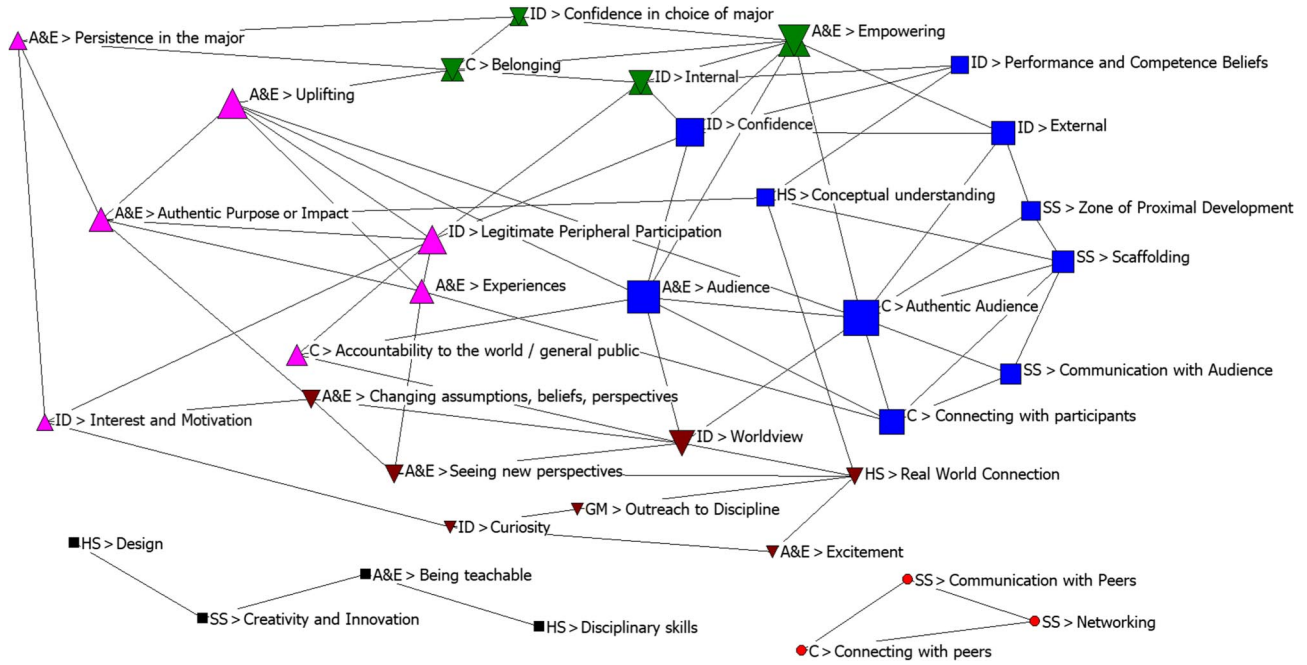


FIG. 1. Network map at the  $p < 0.001$  level of relationships between codes included in this study. The title of each node includes the category that the code is from, nondisciplinary skills (SS), disciplinary skills (HS), affect and experience (A&E), community (C), identity (ID), and mindset (GM); as well as the name of the code. Codes with no statistically significant relationships to other codes are omitted. The size of codes is representative of their eigenvector centrality. Codes are grouped into clusters (by color and shape) using a Girvan-Newman clustering analysis with  $Q = 0.476$ .

After participating in outreach, one student in particular summarized these impacts in informal physics programs thusly:

I feel better involved in my major, and I feel more self-assured as a physicist. I truly feel like I have picked the right major that aligns well with what I can do and what I am interested in doing.

Another student went into greater detail, sharing how in their freshman year they felt like “just another physics major” and that they perceived themselves at that time to be “nothing special.” However, once they started facilitating outreach, this idea of “not being special or notable was completely wiped out” of their mind. They “no longer felt like just another average physics student. Outreach gave [them] a sense of belonging and purpose.” Their experience led them to be recognized by others in the department, both faculty and students, and become a physicist that the department could depend on. This highlights a significant shift in their internal perceptions of themselves, which they attribute heavily to outreach, culminating in a sense that they are “worthy of the title of a physics major.” Other respondents in this cluster were briefer in their comments but repeatedly identified that outreach validated, reinforced, or affirmed their choice in major. In the words of one student, “if I had to do life over again, I’m pretty confident that [I] would choose physics again.” From the

emergent themes of codes within this cluster, it was termed *resilience*.

## 2. Red inverted triangle cluster: Transformation

The cluster comprised of dark red inverted triangle icons contained codes: curiosity, worldview, excitement, changing assumptions, beliefs, and perspectives; seeing new perspectives, and growth mindset—outreach to discipline. As a whole, the codes related to shifts in students’ outlook on their path in physics, a redefining of what it means to be a physicist, or about the malleability of their skills within the discipline (indicative of a growth mindset). Regarding outreach, respondents attributed these changes to their intrapersonal or interpersonal experiences related to outreach events and programs.

For some students, their engagement in informal physics programs was observed to act as a way to put their current knowledge in context. As one student shared, “I realize[d] how little I actually know and wish to expand that knowledge.” Others began to see themselves in different ways than they had before. This was exemplified by students sharing that they “still have a ways to go, but [they] have grown to see [themselves] as someone who shared knowledge with others” or that they were “reminded how far [they] have come in [their] understanding of physics/astronomy” when communicating it to others. For other students, this change in their outlook addressed

their feelings of imposter syndrome. In particular, multiple students shared that by communicating physics to the public it had helped them to “come to terms” or “alleviate” their imposter syndrome. One respondent in particular elaborated on how they “did not feel the need to compare [themselves] to the incredibly bright people in [their] department. [They] feel more secure in [their] identity as a physicist.” Outreach also had an impact on students’ worldview, helping some to “understand the vitality of science communication” and how “valuable a skill” that can be for a physicist. Through growing that skill set, students may experience personal growth where they “no longer feel like just a student in the physics community, but also an active member of it.” From the student experiences evident within this cluster, it was termed *transformation*.

### 3. Blue square cluster: Audience dialogue

The cluster of blue squares was comprised of the codes: authentic audience, audience excitement, confidence, external recognition, performance and competence beliefs, zone of proximal development, communication with audience, connecting with participants, scaffolding, and conceptual understanding. Student experiences evident within this cluster centered on engagement with an authentic and curious public. Their experiences showcased both changes to student self-perceptions as physicists stimulated through this engagement as well as the development of essential career skills around communication. Student shifts in self-perception were focused on awareness of learning physics concepts and on aspects of physics identity, specifically external recognition.

Students reported on their sense of excitement and joy at interacting with the public. From feeling “inspired” by kids asking “fantastic questions,” or seeing “fascinated little faces” when engaging with physics demonstrations, to touching exchanges where a middle school student went up to a facilitator and shared that “he wanted to be a scientist when he grew up” after having so much fun; respondents demonstrated how nearly ubiquitous positive interactions were during informal physics outreach programs. Pushing deeper than the excitement, respondents went on to share their awareness of how they had changed by working with their outreach programs. Regarding career skill development, one student shared how outreach “helped [them] find the correct vocabulary that the general public is comfortable with.” Another contextualized their outreach experience as helping them learn the best ways to interact “with those who both know and don’t know” physics. This also helped to push students to deepen their own understanding of the topic since, as one student put it, having the

opportunity to explain physics in a simplified manner means I need to understand it well so that

it makes sense to younger children or people without science background.

These interactions through authentic exchanges were also observed to help students alter their views of themselves due to the situation and feedback received. From one respondent’s most memorable experience they recalled

talking to one child, being completely engrossed in the explanation, and not noticing until [they] had finished [their] explanation that this was the child of one of [their] professors! [They] gave a much better explanation and demonstration because [they] didn’t realize that there was potentially someone else watching over [them], leaving [them] more relaxed even when talking to influential people in the field.

Another student shared that after having shown a young girl several demonstrations, she went on to

reteach [the respondent] everything [they] had taught the young girl. Her take away from this experience was that she was not only making a difference but proved that [they were] smart and good enough to make a difference.

From the emergent themes within this cluster, it was termed *audience dialogue*.

### 4. Pink triangle cluster: Community participation

The cluster of pink triangles centered on respondents’ experiences specifically with their physics community. The codes within this cluster include: legitimate peripheral participation, authentic purpose or impact, interest and motivation, persistence in the major, accountability to the world and general public, uplifting, and transformational experiences. Respondent experiences within this cluster focused on their integration into the overall physics community through experiences in outreach, as well as transitions of self-perception and persistence in the field. In particular, a theme of self-perception centered on shifts due to accountability and students’ sense of duty to give back to the world through their positionality as members of the physics community. It is notable that, though not present within the network map at the level of significance used for this study, this cluster contains a majority of responses where students referenced a focus on teaching as a future profession.

Through their engagement in informal physics programs, respondents described shifts in their self-perceptions that emerged through interactions with others. One student in particular highlighted that

even though [their] classes are difficult, which can be discouraging, [they] are reminded how far

[they] have come in [their] understanding of physics/astronomy when [they] are teaching others about physics/astronomy topics. This helps [them] feel more like a physicist and less like a floundering student.

Some respondents also spoke of the connectivity they gain through outreach. From one student's experience their

participation in physics and astronomy outreach has added depth to [their] identity as a physicists. It keeps [them] connected to the community.

For at least one respondent, their experiences in outreach provided opportunities to form essential relationships that broadened their roles within the department as outreach "made [them] feel not only as a student, but also a mentor and a mentee to professors and new students that are starting in the field." This is echoed by another response which shared how the respondent realized that they "may be a role model for some." Numerous responses also discussed a feeling of necessity of giving back to the general public as an essential element of being a physicist. As one response framed it, outreach changed their perception

from wanting to just work on the nitty-gritty of research and science collaboration, to acknowledging the great importance of being able to communicate those complex topics to a general audience.

An additional theme from this cluster showed that through their community engagement a number of respondents experienced a growth or reinforcement of their desire to teach physics in the future. After working with outreach programs, some respondents shared that they could "actually see [themselves] teaching physics in the future" or that working with elementary-aged students and seeing the looks on the kids' faces "really validated [their] goal of becoming a physics teacher." One in particular shared how through outreach they "found that [they] liked talking about research far more than doing research" and this had helped them "chose teaching as [their] ultimate career goal." From the themes evident within this cluster, it was termed *community participation*.

### 5. Black square cluster: Disciplinary development

The cluster comprised of black squares contains codes: design, creativity and innovation, being teachable, and disciplinary skills (related to applying physics knowledge). Together, these codes related to constructionist impacts through creation activities, which contributed to enhancing students' physics knowledge. A majority of experiences shared by respondents centered on their work building or creating demonstrations for use in outreach events.

This cluster is perhaps best summarized by one student's experience that

Outreach has made me more confident in my perception as a physicist. I am able to create something, learn from its creation, and then present my knowledge to the public.

Another student added to this idea that creating a demonstration required them to see "how feasible and practical the theoretical knowledge" can be. Here we see evidence of the direct link between creating and learning, as well as development of confidence seen in another cluster. Through the eyes of other respondents, this process of creation was also seen to "not only test my physics knowledge but also my creativity" or that "turning an idea into a tangible, working creation and the work involved in that allowed me to utilize my physics knowledge in a real-world setting." These activities are then seen to further physics knowledge by developing creative new solutions, which must of course "effectively communicate the concepts." This process is not necessarily a quick one either, potentially overflowing from a traditional semester as seen with one student who "had spent the year designing" a significant astronomy-based activity. While not all facilitators of outreach engage in a design process or create new demonstrations, some do. Students reported that this process helped them be cognizant of how they are "absorbing the knowledge" from classes and allowing them to push their boundaries "getting practical knowledge" in bringing a demonstration to life, deepening their understanding of specific physics topics while developing their skills of creativity to share something with their audience. The emergent themes within this cluster led to its labeling as *disciplinary development*.

### 6. Red circle cluster: Disciplinary connectedness

The final cluster identified by red circles comprised three codes, all interconnected: networking, communication with peers, and connecting with peers. Combined, these codes related to the experiences of respondents in getting to meet and know their classmates, professors, staff, and other departmental personnel in less formal contexts working through outreach events.

This cluster related to two different impacts on students. For some, engaging in outreach helped them to become "[a] more socially capable person that can talk more easily to other physics majors." Multiple respondents discussed the development of their social circle through their outreach connections, highlighting that it helped them to make "so many friends in the department," to "feel better involved with [their] major," or that the "relationships [they'd] built with other participants" had been their most memorable experience through outreach. For others, their experiences

through outreach had a more direct impact on their learning via enhanced interactions related to coursework. As one student shared

without the confidence I gained through outreach, I don't think I would have asked as many questions in class, spoke up in group activities, or had as much confidence in the work I produced. Outreach taught me how to effectively communicate my thoughts to professors and fellow classmates, this skill alone contributed to a lot of my success as a physics major.

Through outreach, this student was better able to engage and speak up with others in their department, enhancing their overall learning. From the emergent themes of this cluster, it was termed *disciplinary connectedness*.

### B. Connections

From Fig. 1 it may be seen that four of the six clusters are connected across multiple edges. A simplified network map highlighting these connections is shown in Fig. 2. These connections demonstrate that the impacts of students engaging in informal physics programs are, mostly, not independent but interrelated. Here, we briefly highlight the experiences of students at the intersections of these four clusters. It is interesting to note that no statistically significant links are present between the *transformation* and *resilience* clusters.

### 1. Community participation—resilience

The *community participation* and *resilience* clusters connect along four edges: persistence in the major—confidence in choice of major, persistence in the major—belonging, legitimate peripheral participation—internal recognition, and uplifting—belonging. Experiences from students which exemplified these connections focused on the importance of engagement within the physics community reinforcing their sense of belonging in physics and/or a desire to complete their studies in the field. Students reported that through engaging in outreach they felt “more accepted in the physics community and also [felt] more motivated to keep working hard on [their] dreams and projects.” Another shared that facilitating outreach helped them feel as if they “belong[ed] more amongst [their] peers after getting to be around them and it's help[ed] give [them] the confidence and drive to complete the major.” Through working with their peers, students were able to engage with colleagues who shared their interests and values, which made them “feel like [they] belong in physics” and that “the more [they] feel like [they] belong the more comfortable [they] feel calling [them]selves a physicist.” These experiences allowed students to feel “more involved in [their] major than before” after facilitating outreach, allowing them to feel comfortable saying “that [they are] a physicist finally.” Going further, one student shared that “once [they] got into outreach this idea of not being special or notable was complete wiped out of [their] mind” and that they “felt important and worth of the title of a physics major.”

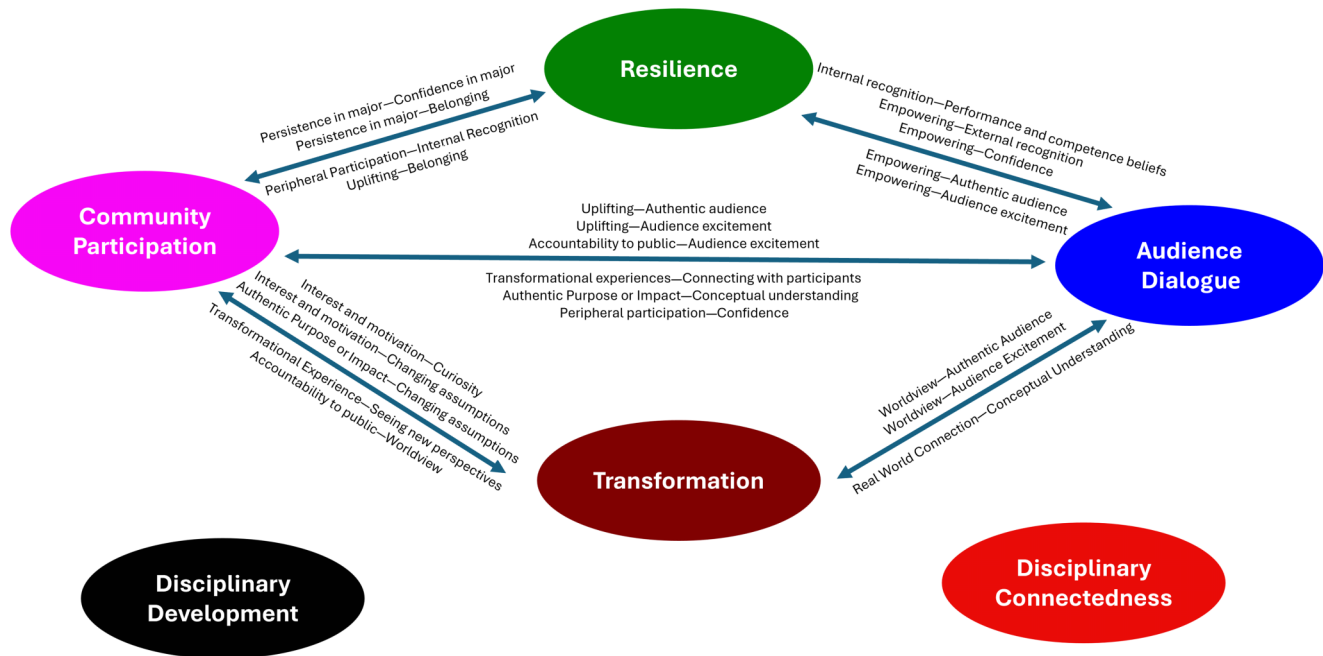


FIG. 2. Simplified version of the network map highlighting the central theme of each cluster and the edges through which the interrelated clusters were connected.

## 2. Resilience—audience dialogue

The *resilience* and *audience dialogue* clusters connect along five edges: internal recognition—performance and competence beliefs; empowering—external recognition; empowering—confidence; empowering—authentic audience; and empowering—audience excitement. Often respondents discussed becoming “more confident” in their knowledge and abilities. They felt “more of a professional in the field when [they] do more outreach programs.” The opportunity to engage with audiences provided a valuable perspective of student capabilities in physics leading to more certainty about persisting in the field. For some, this came about as a reminder that “physics is a source of genuine interest” and that the validation provided by the general public reminded them that they are “not just someone with a passing interest” in physics. These experiences were particularly valuable to one student who felt they did not fit into their department, stating “there are very very few people who look like [them] in [their department],” but that every time “[they met] someone like [them] who’s interested in doing astronomy, [they] feel a little bit more like [they] belong.” One student summarized the impact of this connection very well, sharing that “watching other people’s eyes light up when [they] explain something is a powerful feeling.” This made them “feel more confident since [they] can clearly see that [they’re] capable of explaining” physics. They went on to say that going back over concepts

made [them] feel much more solid in [their] existing knowledge, and has reaffirmed that [they] haven’t gotten dumber as much as the material has gotten more complicated.

## 3. Community participation—audience dialogue

The *community participation* and *audience dialogue* clusters connect along six edges: uplifting—authentic audience; uplifting—audience excitement; accountability to the general public—audience excitement; transformational experiences—connecting with participants; authentic purpose or impact—conceptual understanding; and legitimate peripheral participation—confidence. These links represent perceptions of the progressive integration of students into the physics community through their interactions with the general public through informal physics programs. Many respondents shared inspiring stories of their interactions with audience members, often young children, helping to make them feel more part of the physics community. This could be as simple as “helping younger children see how interesting physics and astronomy is” to specific instances that stuck with respondents. One such example is from a student

working with a high school girl who didn’t even realize you could make a career in physics and

astronomy. She is is now pursuing a physics major in her first year of undergrad and [the respondent is] so grateful [they] got to show her that field.

These interactions can also serve as a measure of student progress within the discipline. One student shared about their experiences in a pen pal program seeking to reduce stigma around physics and astronomy. These exchanges allowed the student to both “watch how much progress [they’re] making toward that goal and [they] get to help a student regain some amount of passion for science,” which they may lose through their regular schooling.

## 4. Community participation—transformation

The *community participation* and *transformation* clusters connect along five edges: interest and motivation—curiosity; interest and motivation—changing assumptions; authentic purpose or impact—changing assumptions; transformational experiences—seeing new perspectives; and accountability to general public—worldview. Numerous respondents reported that outreach helped deepen their passion for their chosen subject, or that they “realized how much [they] love physics.” It also helped some to refine their ideas about what a physicist should be, not just spending all of their time in a lab or engaging in the scientific process but also helping nonphysicists to understand the process and its results. From one student’s perspective outreach helped to show the “disconnect between the way we approach science in academic and the general public’s interest in learning fun science facts.” The student continued saying that it “has helped [them] to take [themselves] less seriously, as... physics is a source of genuine interest for [them] and isn’t always just another academic challenge.” Others went further describing that outreach developed a sense of accountability or need to “communicate and imbue knowledge onto the general public” and that as scientists we should be “helping the general public to understand results and ensuring that science is for everyone.”

## 5. Transformation—audience dialogue

The *transformation* and *audience dialogue* clusters connect along three edges: worldview—authentic audience; worldview—audience excitement; and real-world connections—conceptual understanding. Interactions with the general public helped to facilitate a transformation of respondents’ self-perceptions. This was driven both by direct feedback from members of the audience, as one respondent shared they “didn’t realize how people viewed physicists so highly,” or by bringing physics off of the board and into reality making it “not just a lecture or homework but something that’s real.” Through these interactions, students observed themselves becoming more comfortable being in a position to share their knowledge

and finding ways to make it relevant for those outside the discipline. As one student shared outreach “has shown [them] that there is physics all around us” and they “see it everywhere” they go which leads them to explain the physics to peers even if they aren’t familiar with it. After outreach they can “more easily visualize what physics problems may be describing, and [their] ability to interpret more complex topics has become much easier.” Another reported a similar shift in their abilities stating that they are

now so comfortable explaining a physics concept, that [they] can generally ask someone what they do and find somewhere in their life or career that the specified concept is applied to help them understand it better.

These interactions can also lead to a shift of values for future careers. As for one student, talking to nonscientists “really pushed [them] to consider how [their] physics knowledge can be useful outside of academic” leading them to consider how their work might “improve the life of the average person.”

#### IV. DISCUSSION

As a discipline, physics is often known for having high attrition rates for students who enroll. A swath of literature shows that important factors that can impact students’ choices to persist, or not, within the major relate to their physics identity, sense of belonging, and mindset. Recent work in both K-12 and higher education has noted this effect in other STEM fields as well, particularly when student experiences are limited to courses without pedagogical practices designed to support the development of these constructs [62–65]. When such practices are implemented, students will often experience improved grades, take more challenging classes, and become more resilient to struggle as they move through their education [32,66,67].

As follows from our results, engagement in outreach provides venues for students to find their disciplinary voice, make individual contributions to their home departments, and feel that they belong. By encouraging students to share their passion for and knowledge of physics beyond the classroom, they engage in authentic activities with the general public that convey positive messages and help students develop both their disciplinary identity and sense of belonging. It is notable to observe that the four elements of Hazari *et al.*’s physics identity model (interest and motivation, internal and external recognition, sense of belonging, and performance and competence beliefs) [41] are embedded across three of the four interconnected clusters (*community participation*, *resilience*, and *audience dialogue*) in Fig. 1. These results echo work examining learning assistant programs, which are also seen to enhance student identity and belonging through their activities as near-peer instructors in, and outside of, the classroom [68].

It is worth reiterating the presence of the *resilience* and *community participation* clusters within the network as this has important implications for attrition, or persistence, in physics. Working through informal physics programs provided unique experiences to students which reinforced their confidence in their choice of major and desire to persist in it. This mirrors results from studies in both university and high school settings [13,69,70].

Experiences highlighted in the *transformation* cluster demonstrate how outreach allowed students to develop their own ideas of what it means to be a physicist and how they should engage with the world around them. In particular, this came in parallel to students noticing a reduction to their feelings of imposter syndrome, something common to scientists and professionals at all levels [71–73]. These results mirror our prior work, which saw similar impacts for students who had engaged in outreach [12,13]. Through broadening their engagement beyond their professors and classmates, students receive essential feedback that clearly demonstrates the progress of their knowledge and understanding, which can assault the foundations of imposter syndrome.

The impacts of engagement with a general audience are not limited to mitigating imposter syndrome. As seen in Fig. 1, the cluster of *audience dialogue* is significantly connected with multiple other clusters. Respondent experiences quoted in the Results section regularly attributed the changes in constructs related to their disciplinary identity, belonging, and mindset to the authentic engagement, passion, and recognition they receive from audiences of all ages. Therefore, there is a clear link between the material benefits of student facilitation of informal physics outreach programs with the general public. The impacts observed are an intrinsic feature of these interactions and may not be replicable within a formal curriculum. This importance of audience interactions has been noted by multiple prior studies at single institutions or with small numbers of participants [12,27,29,30].

Feedback from audiences had multifaceted impacts noted in the prior section, being significantly linked to resilience, community participation, and transformation. These interactions allowed for significant opportunities for students to hone and expand their communication skills and to receive strong feedback signals that demonstrate to students how their abilities and knowledge grew with time. By engaging with people beyond the discipline, students received significant opportunities to improve their communication skills, working to make themselves clearly understood at the level of their audience. This vital career skill has been identified as essential to practices for physics students in professional positions [18,19]. These skills are transferable to any profession, whether in industry, government, or academic environments. Indeed, according to work by Sarkar *et al.* [20], communication skills, among others, were noted as being missing or deficient in training

within the major for recent graduate students. Within the context of outreach, students receive authentic opportunities to work on valuable skills, including analogies, illustrations, and explanations [10], which enhance dialogue and understanding with nontechnical audiences. This improvement to communication skills has been noted in prior work [12,13,26] as a result of outreach facilitation. It is important to note that communication was strongly linked to conceptual understanding. As seen in our prior work [8,9], by engaging in the explanation process students refine their own individual ideas and improve their depth of physics knowledge.

Other skills noted as being under taught in the physics curriculum include those of teamwork, organization, and adaptability [20]. By engaging in the process of design and creation, the cluster of black squares termed *disciplinary development*, often for developing an apparatus or demonstration for events, students found themselves honing their creativity and ability to innovate. Outreach is a particularly fruitful place to engage in these activities as coursework and even advanced lab work can tend to be convergent, allowing for only one or two unique approaches. Allowing students to stretch themselves beyond canonical work can provide vital opportunities for discovery, and even low stakes failure, that can be valuable for future careers. Further, the social aspect of outreach allows for significant connections across the department. Indeed, it was evident from several responses that students can make authentic connections with their classmates, with students from other years in their majors, with faculty, and potentially with graduate students and postdocs depending on their institution types. These relationships can, among other benefits, provide opportunities for mentorship in the moment, recently noted as a vital aspect of quality education across their time as students [74]. This is similar to what was observed in our prior work where students reported significant opportunities to work on their creativity through building demonstrations in teams and being able to develop their personal networks across the department [12,13].

Appearance of the code of growth mindset in the network maps complements findings from the regression models conducted on responses to the national survey which showed a statistically significant link between student engagement in outreach programs and signals of growth mindset [28]. These models, however, did not provide the essential nuance of student experiences to fully describe whether participating in outreach helps to develop a students' growth mindset or whether students who already possess a growth mindset are more likely to partake in outreach. Figure 1, however, provides a hint to resolve this question, as the only mindset code present is for growth mindset—outreach to discipline. We assert that this signals a likely explanation of the results from the regression models in our previous study that students facilitating

informal physics programs are more likely to develop a growth mindset. Respondent experiences demonstrate a consistent trend that engaging in informal physics programs helped them to better understand the malleability and evolution of their physics knowledge and abilities. Several responses indicated that outreach helped students develop their growth mindset. They elaborated to share that they felt better able to tackle the challenges of their formal curriculum after this change. This result echoes our previous study which observed women who had engaged in outreach strongly reported signals of growth mindset [13].

## V. LIMITATIONS

The results from open-ended questions posed as part of the national survey exhibit interesting relationships and themes. However, we must appropriately note some limitations in interpreting these findings. All data were self-reported from students responding to the survey. Additionally, the optional nature of the student survey introduces the possibility of selection bias, as students with particularly strong opinions about informal physics programs may have been more likely to respond.

## VI. CONCLUSION

Drawing on the largest national sample available to date, we examined the impact of student facilitation of informal physics outreach programs on constructs of physics identity, sense of belonging, mindset, and career skill development. Students responding to the survey were drawn from SPS chapters throughout the country incorporating experiences from institutions with variably developed informal physics programs. Results from a mixed-methods analysis of responses to three open-ended questions posed to students who had engaged in outreach activities broaden our understanding of impacts on student physics identity, sense of belonging, mindset, and career skill development, with notable parallels to results from our prior single institution study [9,12,13].

Analysis of 239 respondents' answers to open-ended questions relating to their experiences about engaging in informal physics outreach programs has revealed an important set of themes centered on six clusters. These clusters were *resilience*, *community participation*, *transformation*, *audience dialogue*, *disciplinary development*, and *disciplinary connectedness*. The first four of these clusters exhibited multiple statistically significant links, indicating that the impacts described within are not independent of each other. In particular, student experiences of being able to share their physics knowledge and passion with a general audience were linked to higher confidence in their choice of major, sense of belonging to the physics community, and, as a result, characteristics of resilience. Students also felt more integrated into the physics community and practices by being able to inhabit

expertlike positions, and were seen to share higher levels of intrinsic motivation to learn more about their chosen field. Constructs of physics identity [41,42] were distributed through multiple clusters. These codes were heavily interconnected with codes relating to engaging with audience members, indicating that the benefits to enhancing students' physics identity appear to come directly from the nature of outreach which provides flexible ways to engage with nonscientists through low stakes and less structured interactions.

The work of a physicist after graduation relies heavily on skills beyond that of solving physics problems or lab related work. To be effective in the workplace, physics students in the 21st century are expected to gain a broad range of skills including teamwork, communication, and design [16,20]. Results indicate that students gain significant opportunities to broaden and improve their skill sets through facilitation of outreach programs, particularly in communicating with nontechnical audiences, creativity, and networking. Through opportunities to work alongside colleagues in low stress environments, students form potentially long lasting bonds while they explore ways to polish their methods of sharing abstract and challenging ideas in accessible and engaging ways, which often led to improved conceptual understanding. These are skills which are easily transferable to whatever endeavors students pursue after graduation.

Whereas a student just entering the field may see the work of a physicist as one-dimensional efforts in a lab or a chalkboard, those more familiar with the field recognize how limited this view is. Our results indicate that by providing opportunities for transformation, outreach allowed students, early on, to see the breadth and complexity of the work of a physicist and permits them to explore a range of aspects of the field to find what they most identify or resonate with. A particularly important aspect of this is seen by the growth mindset signal which indicates that outreach enriches this perspective of malleability that students can bring back to the classroom.

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## DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain sensitive personal information. The data are available from the authors upon reasonable request.

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