Teacher Characteristics Shape Engagement and Outcomes in Online Professional Learning Environments

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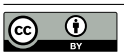
Abstract

This study investigates how certain teacher characteristics—specifically, math anxiety and confidence in teaching mathematics—and school-context features are associated with teachers' behavioral engagement patterns in an online teacher professional learning platform. To this end, we applied frequent sequential pattern mining to elementary teachers' log data collected from an online professional learning platform, the Virtual Learning Community (VLC), and linked it with survey data. Results indicate that teachers with higher levels of math anxiety were significantly more likely to remain within a single section of VLC rather than navigate across multiple sections (b = -0.764, p < .001). Additionally, this exploratory engagement was positively associated with teachers' self-reported instructional practices (b = 0.743, p < .001). This finding indicates that teachers who navigated across multiple sections of VLC were more likely to perceive improvements in their instructional practice. Our research contributes to empirical evidence on how individual differences contribute to diverse patterns of participation in online professional learning, and it discusses practical implications that offer insights for designing teacher-specific support strategies in these environments.



LAK 2026, Bergen, Norway

ACM ISBN 979-8-4007-2066-6/26/04
https://doi.org/10.1145/3785022.3785069

CCS Concepts

• **Information systems** → **Association rules**; • **Applied computing** → **E-learning**.

Keywords

Teacher learning, Sequential pattern mining, Engagement

ACM Reference Format:
Haejin Lee, Amos Jeng, Sarah Burns, Meg Bates, Cheryl Moran, Hana Kearfott, Tiffany Reyes-Denis, Joseph Cimpian, George Vythoulkas, Nigel Bosch, and Michelle Perry. 2026. Teacher Characteristics Shape Engagement and Outcomes in Online Professional Learning Environments. In *LAK26: 16th International Learning Analytics and Knowledge Conference (LAK 2026), April 27–May 01, 2026, Bergen, Norway.* ACM, New York, NY, USA, 10 pages. https://doi.org/10.1145/3785022.3785069

1 Introduction

Professional development and professional learning (PL) experiences for teachers have increasingly moved online, especially since the COVID-19 pandemic [1]. The value of these online PL opportunities is well documented, with studies showing that they can foster teacher development and improve instructional practices [4, 30, 38]. For example, Philipsen et al. [30] found that online PL was crucial in fostering teachers' engagement in reflective strategies, while Marquez et al. [19] emphasized its role in enhancing teachers' self-efficacy and classroom management skills. In addition, online, asynchronous PL opportunities are valuable for teachers who may be too busy to engage in in-person PL experiences.

Despite these benefits of online PL, evidence is limited regarding whether teachers capitalize on these learning opportunities to improve their professional growth, teaching practices, or confidence. Studies have also shown that these factors may in turn impact their students' academic performance, which makes it even more important to understand how teachers take advantage of online PL opportunities [7, 24]. This gap matters because while some teachers may use PL platforms productively and benefit substantially, some teachers struggle to engage with these platforms effectively and miss opportunities to learn online [5]. Indeed, prior studies have highlighted both the low levels of participation and the limited quality of teacher participation in online PL platforms [6, 42].

Therefore, to better support teachers in using online PL opportunities to enhance their professional growth, instructional practices, and confidence, we need to increase our understanding of how they engage with the online PL environment and how their engagement varies with their background characteristics (e.g., math anxiety, confidence, school context). Importantly, elementary teachers are often math anxious [33] and have low confidence in teaching math [11], making them prime candidates for engaging in online PL opportunities that target mathematics confidence and instruction. The question, then, is whether teachers with math anxiety or with low teaching confidence engage with these opportunities in ways that differ from elementary teachers who are not math-anxious or who feel confident in their teaching of mathematics. Additionally, we ask if the school context—e.g., low wages, most students on free or reduced lunch, many English-language learners—has an impact on how teachers engage in an online teacher learning platform. It is possible, for instance, that lack of school resources inhibits teachers from being able to take the time for online PL, or conversely that lack of school resources includes a lack of other PL opportunities and motivates teachers to pursue online PL even more.

In addition to learning who engages with online PL platforms in what ways, it is essential to understand whether different patterns of engagement in online PL environments are related to teachers' perceptions about the impact of that engagement on their mathematics instruction. If teachers who engage more extensively with an online PL platform also perceive impacts of using the PL platform on their mathematics instruction, this would suggest that not just *whether*, but *how* teachers use the online PL platform matters for the intended outcomes. These insights can then help identify which teachers need what kinds of support and guide them to engage with the online PL platform in ways that promote the very outcomes these online PL environments are designed to support.

Our study takes a data-driven approach, using sequential pattern mining, to 1) examine how elementary mathematics teachers engage in an online teacher professional learning platform (TPLP) and 2) how these patterns relate to both teacher background characteristics and their perceived impacts, as measured through self-reported surveys with 243 teachers. In doing so, we contribute to theories of teacher online professional learning and provide practical, actionable insights into how future TPLPs can be designed to support teachers in ways that directly improve their mathematics teaching and confidence.

Thus, we ask the following research questions:

- **RQ1.** How are teachers' self-reported background characteristics (math anxiety, confidence in teaching mathematics, and presence of different identified school-based context features) related to their engagement patterns on the TPLP (e.g., exploratory, single-focused, or resource-focused)?
  H1. We expect that teachers with different background characteristics will use the TPLP in distinct ways, reflected by how they navigate its various sections. For instance, we anticipate that teachers' navigation sequences following visits to the Professional Development (PD) modules will vary based on their level of teaching confidence. Specifically, teachers with lower teaching confidence, or higher math anxiety will be less likely to engage in exploratory sequences that transition from PD modules to other sections of the platform (e.g., PD to online Resources or PD to Discussion) compared to teachers with more experience, higher confidence, or lower math anxiety. We expect these teachers to exhibit single-focused engagement patterns (e.g., remaining within the PD section), likely due to limited experience, confidence, or anxiety that limits their exploration beyond the familiar sections.
- **RQ2.** How are teachers' engagement patterns on the TPLP related to their self-reported impact measures (e.g., instructional practices, students' performance, classroom in general, and confidence in teaching mathematics)?
  H2. Teachers who exhibit single-focused engagement patterns will report lower levels on self-reported impact measures, particularly in areas such as instructional practices and confidence in teaching mathematics, compared to teachers with exploratory or resource-focused engagement patterns.

2 Related Work

In the context of this study, we rely on both Opfer and Pedder's [27] theory of teacher professional learning and Lave and Wenger's [15] theory of situated learning. Following Opfer and Pedder, we highlight the complex ways in which the teacher, the school, and the learning activity reciprocally combine to impact teacher learning. We acknowledge that the learning activity (i.e., acquiring new knowledge about teaching mathematics and about elementary school students' learning of mathematics) is influenced by both the teachers themselves (in this case, their math anxiety and level of confidence in teaching math) and the school context (including institutional supports and constraints, as well as the students in their classrooms). Lave and Wenger's idea of legitimate peripheral participation is also useful in guiding our work, in that teacher learning in an online context necessarily involves peripheral participation, and teachers will take up the ideas and practices that make sense to them, given their perceived needs and backgrounds, and within their context (harkening back to Opfer and Pedder's theory).

2.1 Engagement in online professional learning platforms

Teachers engage in online PL environments in diverse ways, ranging from passive consumption of information or resources to active contribution and participation [9, 17]. Some teachers demonstrate

only shallow or surface-level engagement, such as logging in primarily to share or download resources or to read others' comments [5, 14]. In an analysis of an online PD community, Chen et al. [5] found that teachers often repeated such shallow participation behaviors (e.g., viewing or sharing resources) and rarely engaged in collaborative practices such as participating in discussion. This finding aligns with prior research finding generally lower engagement in online PL environments compared to face-to-face environments [25]. Moreover, teachers (and other online learners) may never leave a footprint—in terms of comments, discussion forum posts, or uploaded documents—on the websites they access, but instead simply "lurk" on the website [39].

By contrast, some teachers proactively explore and engage across multiple sections of PL platforms [26]. These activities include moving between different areas of the platform, such as watching professional development videos, searching for and downloading resources based on their needs, and participating in discussion forums. Such active, cross-sectional participation can act as a bridging role in PL communities. For instance, Anderson and Williams [2] identified teachers acting as "connectors" who navigate across PL spaces, bridging information and disseminating resources and ideas, roles often adopted by veteran teachers. Similarly, Trust [36] found that teachers who participated more actively in online mathematics PL communities reported gains in motivation, empowerment, and changes in their teaching practices. Together, these findings suggest that exploratory, cross-section engagement, connector/bridge roles, and sustained engagement are components of effective PL.

Prior studies have also examined how teachers' engagement in online PL environments can be classified into various types of engagement. For example, Chen et al. [5] categorized teachers' operational behaviors on PL platforms into shallow participation and deep engagement. Shallow participation included relatively passive actions such as only downloading or sharing resources, whereas deep engagement encompassed richer forms of interaction, including discussion participation and collaborative teaching and research. Building on this literature, we focus on three engagement patterns to examine teachers' engagement on the TPLP. The single-focused pattern refers to activity concentrated in one area of the TPLP, which represents a narrow form of engagement. While not identical, this pattern echoes the idea of peripheral participation, as it captures constrained engagement within a limited area of the platform [15]. The exploratory pattern involves navigation across multiple sections of the TPLP, resembling connector or bridge roles that explore and potentially link different parts of the PL communities. Finally, the resource-focused pattern reflects the retrieval and reuse of materials on the TPLP, often characterized by targeted searching and resource seeking [26, 36].

2.2 The impact of teachers' backgrounds on their use of teacher learning platforms

Online teacher professional learning platforms provide important spaces for teachers to learn, and to reflect and collaborate online (e.g., [30, 37]). However, teachers' interest and persistence in these platforms depends, at least in part, on their local context [21]. In a scoping review, Dille and Røkenes [8] found that factors like teachers' backgrounds and attitudes were crucial for success with PL. In these ways, both teachers' school contexts and their own learning needs and concerns (including math anxiety; see, e.g., [33]) constrain and guide their learning on PL platforms. Thus, by examining the relation between teachers' backgrounds and their engagement patterns on an online teacher professional learning platform, we can inform the development of these platforms to support teacher PL more effectively.

2.3 Mining behavioral sequences from log data

In learning analytics, sequence analysis of trace data has become an established approach for examining how students engage and study in online learning environments [3, 34]. Unlike static measures such as counts of clicks or total time spent, sequential analyses capture the order and transition of actions, which provides a temporal perspective on how learning behaviors unfold in digital environments [18, 23]. A range of methods have been used, including process mining, lag-sequential analysis, Markov models, and sequential pattern mining algorithms [13, 32]. These approaches have been widely applied to student log data from intelligent tutoring systems and online learning platforms to identify common sequences of actions and to better understand learning processes, such as collaborative learning and self-regulated learning [16, 29]. Additionally, insights into how learning behaviors unfold through sequences provide practical implications for designing more effective learning environments, such as tailoring support by suggesting engagement behaviors that foster effective learning strategies [31].

Despite the extensive body of work using student behavioral data, relatively few studies have applied these techniques to examine how teachers engage in online PL environments. Research on teacher engagement in online PL spaces has primarily relied on frequency-based indicators [5]. For instance, participation is often measured by counting visits, posts, or comments, which provides only a partial view of engagement. Such measures overlook how teachers move across different sections of PL platforms and the sequences of actions they perform. However, examining how different sequences of actions unfold, and how these pathways relate to professional outcomes, is essential for understanding the mechanisms through which online PL platforms contribute to teacher development. This, in turn, can help design support that recommends subsequent actions likely to assist teachers in achieving their learning goals.

2.4 Engagement patterns and perceived impact

Investigating the effectiveness of PL platforms from teachers' perspectives is also important for understanding their actual benefits to teachers [22, 28, 35]. However, even if teachers report positive impacts, it is more important to know whether and how those reported outcomes are connected to what the teachers do, through their observable behaviors in online PL spaces. Having this insight is crucial for identifying which types of engagement are most beneficial and for determining how teachers can be supported in achieving their goals in PL environments.

Prior studies have found positive impacts of online PL opportunities on teachers' knowledge, instructional skills, and confidence [12, 20]. For instance, Trust [36] found, via self-report, that teachers' active participation in an online mathematics community was

associated with higher motivation, empowerment, innovation, and changes to teaching and learning. While these survey-based insights are valuable, in many online contexts these measures are not available, which makes it difficult to detect how teachers' engagement relates to the benefits they perceive from using PL platforms. Additionally, limited studies have combined log-based analyses with self-reported outcomes, which could provide opportunities to measure engagement patterns from log data. In this study, we leverage a data-driven approach to identify engagement patterns and the relationship between those patterns and teachers' self-reported background characteristics. The practical insights from our findings can guide the design and development of targeted supports that foster meaningful engagement and help teachers use PL platforms in ways that support them in meeting their goals.

3 Method

In this section, we describe the Virtual Learning Community (VLC), the online professional learning website used in this study, along with the data collected, the measures of teachers' background characteristics and perceived impacts, and the analytical approach employed. This study was preregistered on the Open Science Framework (OSF; link).

3.1 Research context

VLC has over 68,000 members and has sustained teachers' engagement with and learning from lesson video and other artifacts for more than 10 years. The site is open to all and free of charge to anyone who registers as a member. Teachers engage with VLC asynchronously, on their own, for their own learning goals. There is no facilitator beyond the prompts and other framing provided with the site's resources. The site includes PD modules, a resource library, and discussion forums—each of which are described more below:

There are two different types of PD modules: public and private. The public modules are self-paced and structured as short lessons that integrate brief readings, videos of classroom teaching and professional development, and assignments which include reflective prompts and questions to check for understanding. The private PD modules consist of recordings of online professional learning conferences, along with related resources and assignments, and are available only to those users who have paid for access.

The Resources library is organized into several sections that support teachers' learning and teaching practices. Collections group together videos and resources by topics relevant to elementary mathematics teachers, such as support for e-learning, collaborative coaching, and deepening teacher understanding of the standards for mathematical practice. Other sections include newest content and teacher-shared resources. The library overall provides curated lesson artifacts and classroom teaching videos alongside teacher-contributed materials. The Resources library includes a search bar (see Figure 1) to assist users in finding resources relevant to their questions or needs. Users can download resources and can save them for future reference, and they can also upload their own resources. The Discussion forums contain topic-specific and grade-level groups where teachers can post and answer questions, share experiences, and provide feedback on resources (see Figure 1).

3.2 Data collection and participants

We collected two types of data: 1) trace data, which recorded teachers' observable behaviors on the platform (e.g., which sections they accessed) between August 2023 and May 2025; and 2) survey data, which recorded teachers' demographics (including school context features), background characteristics (e.g., math anxiety and confidence in teaching math), and impact measures (e.g., instructional practices, student performance, classroom environment, and confidence in teaching mathematics). The survey was completed by 243 VLC users, whereas the trace data encompassed a broader number of users (N = 4,252) because we extracted frequent interaction sequences from the 2023–2025 log to obtain a comprehensive set of frequent interaction sequences (see Section 3.5.2). For all regression analyses linking engagement patterns to background characteristics and perceived impacts, we restricted the sample to survey respondents and computed the number of occurrences of engagement patterns per teacher using logs from the survey-aligned time window (August 2024 through May 2025).

The log data recorded teachers' observable behaviors on VLC as timestamped page visits. For each visit, we recorded the associated URL, which allowed us to map it to the section of VLC the teacher visited. For the PD modules and the Discussion section, we used the top-level path (e.g., "/pd", "/discussion") to identify the sections teachers visited. Because the resource library contains multiple distinct features, we extracted one additional level within the Resources path (e.g., "/resources/search", "/resources/download", "/resources/collections") to distinguish searches, downloads, and collection browsing.

3.3 Data preprocessing

We preprocessed logs collected between August 2023 and May 2025 (N = 228,091 rows). The goal of data preprocessing was to remove telemetry events and apply a duration threshold to the log data which was necessary to ensure that the resulting log contained only meaningful page visits (i.e., interaction lasting more than 5 seconds) rather than accidental clicks. We excluded telemetry logs (e.g., /non-video-resource-vimeo-video-track, /resources/<id>/track), resulting in the removal of 80,750 rows. For each remaining row, we computed time on activity as the elapsed time to the next event. A supplementary table summarizes the organization of logs for each section of VLC (Appendix Table 2).

Short visit durations were common in logs, which may reflect accidental clicks, rapid back/forward navigation, or page reloads than actual engagement. We therefore set a 5-second minimum threshold to filter out possible incidental interactions from log data. Some activity types (e.g., login, resource download, profile editing, login) do not require time spent duration to be meaningful, so we did not apply the minimum time threshold to these activities. Instead, the 5-second threshold was applied only to activities where time spent is relevant for interpreting engagement, such as working within Online-PD (both private and public), browsing or accessing resources, and participating in discussions.

3.4 Survey measures

To answer RQ1, teachers' math anxiety was measured as the mean score of nine items rated on a 5-point Likert-type response scale

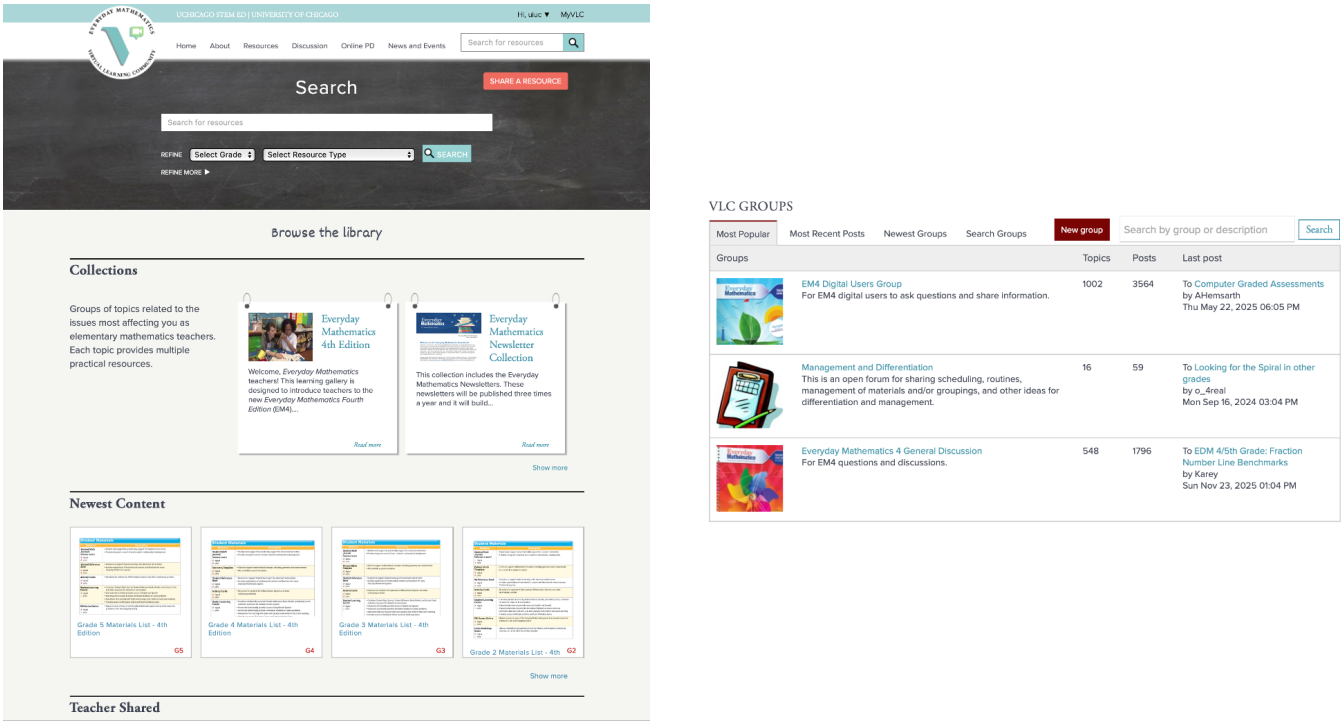


Figure 1: Screenshots illustrating the Resources library (left) and the Discussion forums (right). Portions that may reveal the identity of the website are covered.

(e.g., "My palms start to sweat if I have to do a difficult math problem."), and confidence in teaching mathematics was measured using a single 5-point Likert-type item ("How confident do you feel about teaching math in general?"). Math anxiety was measured using a validated scale developed by Ganley et al. [10] and confidence in teaching mathematics was assessed as a reliable indicator by examining its positive correlation with teaching enjoyment and negative correlation with math anxiety.

We analyzed teacher-reported school-context features to see how many of those indicated that their teaching settings may be low- or underresourced schools. To do this, we summed the presence of four conditions, each coded as a binary variable (1 = present, 0 = not present): (1) the school where the teacher teaches is located in a rural area, (2) more than 50% of students receive free or reduced-price lunch, (3) more than 50% of students are non-English-speaking, and (4) full-time teachers at the school earn less than $44,000. The impact measures were developed specifically for this study and were informed by prior literature on teacher professional learning and classroom practice [21]. This resulted in a count ranging from 0 to 4, indicating how many of these conditions were present at the school. For RQ2, we used teachers' self-reported impact measures, based on survey questions that asked whether using VLC had influenced four areas: instructional practices, students' performance, classroom environment, and confidence in teaching mathematics. Each item was coded as a binary variable, indicating whether teachers reported an impact in that area.

3.5 Analytical method

To examine the relationships between teacher characteristics and engagement patterns (RQ1), as well as teachers' perceptions of the impact of that engagement (RQ2), we followed four steps. First, we constructed three engagement categories (i.e., exploratory, single-focused, resource-focused). Second, we extracted teachers' frequent interaction sequences by applying the constrained sequential pattern discovery algorithm (cSPADE; [40, 41]) to the log data. Third, we assigned interaction sequences to one of the engagement categories defined in the first step, in consultation with VLC experts (including the original designers of VLC). We then conducted regression analyses relating survey measures to the count variables of engagement patterns. The following subsections elaborate on each step.

3.5.1 Constructing engagement pattern categories. We constructed three engagement pattern categories (i.e., exploratory, single-focused, and resource-focused), based on our preregistered plan, prior work, and the functional structure of VLC. VLC includes six top-level sections (i.e., Homepage, About, Resources, Discussion, Online-PD, and News & Events). The three engagement pattern categories focus primarily on interactions in Resources, Discussion, and Online-PD as these sections contain rich Resources (described in section 3.1), whereas Homepage, About, and News & Event are primarily static informational pages, and exhibited low variance and sparse event types in preliminary analysis. The exploratory engagement category represents cross-section navigation (e.g., Online-PD → Resources, Resources → Discussion) rather than remaining within

a single section. This pattern reflects the platform's intended learning pathway, articulated by the original designers of VLC (who are also authors of this study): encountering new ideas in Online-PD, locating and examining relevant resources, and engaging in Discussion forums. We treat exploratory sequences as indicators of breadth and bridging across sections that align with the platform's intended design to assist teachers' learning and teaching practices.

The single-focused engagement pattern category refers to interactions that remain confined within a single section of the platform, such as staying exclusively within the Online-PD modules or the Resources page. According to the original designers of VLC, this pattern reflects a focused but limited mode of engagement, where users draw on the platform in a targeted manner without transitioning across different types of learning opportunities. We note that the single-focused engagement pattern category did not include any activities within the Resources page. We treated Resources as a separate engagement category because our previous study showed that teachers predominantly engaged with the Resources section and that transitions among them are particularly indicative of self-regulatory behaviors such as planning, strategic resource selection, and monitoring. The Resource Library encompasses multiple distinct functions within a single area (e.g., search, download, collections; see Section 3.1). Thus, classifying resource-centric sequences as merely "single-focused" would risk obscuring important within-resource behaviors.

3.5.2 Sequential pattern mining. After constructing the engagement categories, we segmented the preprocessed log data (section 3.3) into sessions using a 30-minute inactivity threshold. If the interval between two logged activities (e.g., visiting a PD module page or searching Resources) exceeded 30 minutes, we treated this as the end of one session and the beginning of a new one. For instance, if a teacher visited an Online-PD module, remained inactive for more than 30 minutes, and then later returned to search for resources, the activities before and after the inactivity period were treated as belonging to two separate sessions. This approach was to ensure that the resulting sequences reflected continuous engagement within the platform, based on exploratory data analysis showing that 30 minutes was approximately the point at which consecutive actions no longer appeared to be part of the same learning session. We then transformed the logs into a long format in which each event (i.e., one interaction activity such as visiting a PD module page or a Discussion forum) included a teacher ID, a log activity, and an order ID indicating its position within the session. For instance, if a teacher's first activity in a session was visiting the main Resources page, it was assigned order ID 1, and a subsequent action by the same teacher within the same session, such as searching for resources, was assigned order ID 2.

We applied cSPADE to these session-based sequences with a minimum support of 5% (i.e., sequences appearing in at least $\geq$ 5% of sessions) and without allowing gaps between successive elements in a sequence. This ensured that only frequent and continuous interaction sequences were retained. The algorithm returned frequent navigation sequences along with their support values. For instance, given a set of session-based log sequences, cSPADE produces a list of frequent and continuous interaction patterns such as Online-PD $\rightarrow$ Online-PD or Groups $\rightarrow$ main Resources page, each accompanied by a support value indicating the proportion of sessions in which that exact sequence occurs.

To categorize these sequences into constructed engagement categories (i.e., exploratory, single-focused, and resource-focused), a group of three experts, including a PhD student responsible for the analysis and two of the original designers of VLC, reviewed the extracted interaction sequences. We followed a consensus coding approach in which the experts jointly reviewed the extracted frequent sequences and determined how they mapped onto the predefined categories by examining how the sequences reflected teachers' interactions within VLC. This approach was intentional because interpreting extracted sequences requires domain expertise and contextual knowledge of VLC's design, which cannot be reliably captured through automated methods. Although the engagement categories were pre-defined, applying cSPADE provides empirical grounding by demonstrating that these engagement categories reflect recurring behavioral patterns in the log data that are not easily identified through manual inspection.

3.5.3 Regression Analysis. To answer RQ1, we fit negative binomial regression models in R to examine whether teachers' background and school context characteristics predicted the number of times each engagement pattern was used. Because the dependent variables are count data and not normally distributed, negative binomial regression was appropriate for answering our research question. We treated the number of times each engagement pattern was used by individual teachers as a separate dependent variable and fit separate regression models for each engagement pattern category. For RQ2, we fit a logistic regression model in which the dependent variable was teachers' perceived impact (e.g., instructional practices, students' performance, classroom in general, and confidence in teaching mathematics), and the independent variable was the number of times each engagement pattern was used by individual teachers.

4 Results

In this section, we present descriptive statistics, followed by the results for each research question.

4.1 RQ1: Relationships between teacher characteristics and engagement patterns

4.1.1 Engagement pattern categorization. To address our first research question, which examines the relationship between teachers' background characteristics and the ways they engage in VLC, we categorized frequent interaction sequences identified through sequential pattern mining into three engagement patterns: exploratory, single-focused, and resource-focused (Table 1). In sequential pattern mining, the support value itself represents an effect size, which is reported in Table 1. The support value indicates the proportion of sessions in which a given interaction sequence appears at least once.

Exploratory engagement included sequences where teachers moved across sections of VLC, most often between Online-PD modules and the Resources section (e.g., Online-PD $\rightarrow$ main Resources page $\rightarrow$ Resources search; support = .052) or between Discussion groups and Resources (e.g., Groups $\rightarrow$ main Resources page; support

= .142). Conversely, single-focused engagement patterns included sequences we found to be quite common where users confined their actions to a single section, such as repeated visits to Online-PD modules (Online-PD → Online-PD; support = .146) or extended use of Discussion forums (Groups → Topics; support = .156). Finally, resource-focused engagement consisted of sequences concentrated within the Resources section, including searching, viewing, and downloading materials (e.g., Resources search → Resources search → specific resources page → Resources download; support = .346). These we counted separately from other single-focused patterns, given the specific popularity of the Resources section.

4.1.2 Background characteristics and engagement patterns. Among teachers' background characteristics, we found significant associations for self-reported math anxiety scores and teaching confidence, but not for the school context factors. Engagement in the single-focused pattern was positively associated with teachers' self-reported math anxiety scores (b = 0.152, *IRR* = 1.164, 95% *CI* [1.007, 1.345], p = .040). This positive association suggests that teachers with higher math anxiety are more likely to remain within a single section of VLC (e.g., staying only within the Online-PD module) rather than navigating to other sections of VLC. Teaching confidence showed the opposite pattern and was negatively associated with single-focused engagement pattern (b = -0.764, *IRR* = 0.466, 95% *CI* [0.359, 0.605], p < .001), indicating that teachers with lower confidence are more likely to remain within a single section of VLC. In contrast, there was a significant positive relationship between self-reported teaching confidence and the resource-focused engagement pattern (b = 0.320, *IRR* = 1.377, 95% *CI* [1.054, 1.804], p = .019), suggesting that teachers who feel more confident in their teaching mathematics are more likely to actively seek out and engage with instructional resources within VLC.

4.2 RQ2: Engagement patterns and perceived impacts

Although RQ1 examined how teachers' background characteristics relate to their engagement with VLC, it does not indicate whether these engagement patterns are associated with teachers' self-reported impacts of using the platform. Therefore, in RQ2 we extended our analysis by examining whether different engagement patterns were linked to teachers' self-reported impacts across four aspects: instructional practices, students' performance, the classroom, and confidence in teaching mathematics. We found that exploratory engagement was positively associated with teachers' self-reported instructional practices (b = 0.743, *OR* = 2.103, 95% *CI* [1.636, 2.703], p < .001), suggesting that teachers who navigated across multiple sections of VLC were more likely to perceive improvements in their instructional practice. In contrast, no significant associations were observed between engagement patterns and self-reported impacts on students' performance.

Resource-focused engagement was significantly positively associated with teachers' perceptions of classroom impacts (b = 0.048, *OR* = 1.050, 95% *CI* [1.019, 1.081], p = .001), indicating that teachers who engaged more extensively within the resource section, such as searching, revisiting, and downloading materials, were more likely to report that VLC had impacted their classroom in general. Resource-focused engagement and exploratory engagement were positively associated with teachers' self-reported confidence in teaching mathematics (resource-focused: b = 0.026, *OR* = 1.026, 95% *CI* [1.009, 1.052], p = .048; exploratory: b = 0.189, *OR* = 1.208, 95% *CI* [1.109, 1.254], p = .018).

5 Discussion

We discuss the summary of our results and implications for each of RQ results. In this study, we identified consistent patterns of use for an online teacher professional learning platform by teachers in elementary schools: those who stayed in one area of the website, those who utilized multiple resources, and those who traversed multiple sections of the website. We found that teachers with higher levels of math anxiety and with lower levels of confidence were significantly more likely to remain within a single section of VLC, typically the online professional development module, than navigating across multiple sections of VLC.

5.1 Teacher backgrounds and their engagement in PL

This research makes clear that teachers' own backgrounds and their school contexts can constrain their opportunities to make productive use of resources that have the strong potential to support their learning and growth, and ultimately to improve their practice and advance their students' learning of mathematics. As Opfer and Pedder [27] noted, school context, the teachers themselves, and learning online must be considered together to understand teachers' PL. Indeed, lack of resources, math anxiety and lack of confidence can work to block teachers' productive use of a valuable resource to support their PL. Thus, improving teacher PL must understand how these features work in concert to support teacher learning.

Our results have practical implications and suggest that teachers' individual differences and contextual factors should be taken into account when developing teacher-specific support strategies in online professional learning settings. For example, these platforms could incorporate prompts to encourage broader exploration among teachers who may otherwise remain narrowly engaged and miss opportunities to benefit from the diverse resources available across different sections of the platform, supporting their professional growth and instructional practice.

5.2 Perceived outcomes and their relation to engagement patterns

Our analysis of RQ2 showed that teachers' patterns of engagement in PL spaces are related to how they perceive the platform's impact on their instructional practice, classroom environment, and confidence in teaching mathematics. These findings are consistent with prior studies that reported effects of online PL on teachers' knowledge, instructional skills, and confidence [12, 20, 36]. However, our findings extend this line of work by demonstrating that perceived benefits are associated with teachers who actively engage in bridging roles [2]. For instance, by connecting professional development modules with relevant resources and discussions, teachers may translate abstract ideas into concrete classroom strategies and improve their instructional practices. Similarly, teachers who adopt resource-focused strategies [26, 36], such as retrieving and reusing

Table 1: Engagement categories and relevant interaction sequences. Higher support values reflect larger effect sizes of interaction sequences and more prevalent behavioral patterns

Engagement category	Relevant interaction sequences with support
Exploratory	Groups → Main Resources page (.142) Resources search → Online-PD (.154) Online-PD → Main Resources page → Resources search (.052) Online-PD → Resources search (.145) Resources search → Groups (.049)
Single-focused	Online-PD → Online-PD (.146) Groups → Groups (.089) Groups → Topics (.156) Paid Online-PD → Online-PD (.060)
Resource-focused	Main Resources page → Resources search (.554) Resources download → Resources search (.368) Resources search → Resources search → Specific Resources page → Resources download (.346) Resources download → Main Resources page (.200) Collections → Collections (.151)

materials, may employ these resources to prepare lessons by adapting instructional content to their classroom environment.

6 Limitations and future work

In this study, we focused on a single online professional learning platform (VLC). Future research could examine whether the patterns we observed hold across other online professional development platforms that differ in design or content, or if not, what aspects of PL platforms predict differences in how teachers use those platforms. Additionally, in future work we plan to extend the analyses to more characteristics of teachers that could explain differences in how they use PL platforms. This paper is one of the first to analyze teacher-level differences in usage of PL platforms, so there is much yet to discover; for example, could school size affect teacher usage if teachers in some schools need to rely more on online PL platforms due to fewer available peers? Could student demographics shape teacher usage, if, for instance, teachers seek specific resources from PL platforms to help students who are learning math with English as a second language? The current study targets a few characteristics that we anticipated (and preregistered) would be the most impactful, but future exploratory work should be done to discover a broader range of relevant teacher characteristics and their causal relationships to online PL platform usage.

This paper is also limited in scope to quantitative analyses, which offer breadth and statistical power to generalize findings to the broader population of VLC. However, these quantitative methods alone do not offer the depth that could be possible with qualitative methods, to understand more about teachers' reactions and thought processes while using VLC. In future work, we plan to conduct qualitative analyses of one-on-one interviews with teachers, which will reveal more about their experiences of using VLC and could also generate new ideas for teacher characteristics to consider in explaining the variance of how teachers use online PL platforms.

7 Conclusion

Teachers increasingly rely on online PL platforms to fulfill professional development needs, find resources to use in their classes, and discuss teaching with their peers. However, little is known about how, exactly, they engage, what explains variance across teachers in their engagement, and whether teachers perceive such engagement with online PL platforms as helpful. Thus, in this study we quantified teacher engagement in one such platform, VLC, via sequential pattern mining, and compared those patterns with teachers' background characteristics and school context variables to understand more about how PL platforms can better serve teachers. Indeed, both exploratory and resource-focused engagement patterns were positively associated with teachers' perceived improvements in instructional practices, classroom dynamics, and confidence in teaching mathematics, showing that the manner in which teachers use online PL platforms is significant. We anticipate that the future of online PL platforms will involve learning analytics to detect cases where teachers could benefit from personalized intervention based on these findings—for example, nudging new, underconfident teachers toward exploratory behaviors that reveal more about the resources PL platforms have to offer—ultimately leading to improved teaching, teacher confidence, and student learning.

Acknowledgments

This material is based upon work supported by the National Science Foundation under Award No. 2301272.

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A Information on log data activities

Table 2: Observable log activities by sections of the VLC. The table categorizes observable log activities by the VLC sections in which they occurred. For example, the Resources section includes all log activities observed within that part of the platform.

Section of VLC	Observable log activities	Description
Online-PD (n = 17,511)	Paid online-pd; Online-pd	Accessing or completing paid online-pd modules; engaging in public online-pd modules such as watching videos or reading descriptions; teachers engaging in assignments or activities within online-pd modules.
Resources (n = 87,082)	Main resources menu; Specific resources page; Resources rate; Resources search; Collections; Resources download; User uploaded documents	Browsing the main resources menu; viewing specific resource pages such as classroom videos or teacher-shared resources; rating viewed resources; using the search box to find resources; exploring collections related to teaching topics; downloading specific resources; uploading user-created resources.
Discussion (n = 8,277)	Groups; Topics; Subscribe to discussion updates	Browsing or searching discussion groups where teachers can ask or respond to questions; viewing specific discussion threads; subscribing to discussion forums.
Home (n = 9,420)	Homepage	Visiting the VLC homepage.
About (n = 286)	About	Browsing the page describing the VLC.
News and Events (n = 896)	News; Events	Accessing pages related to platform news or upcoming events.
Website-level activities (n = 4,543)	My account; Edit profile; Update user profile	Accessing account settings; editing the user profile; updating personal profile information.