Pushing Frontiers in Teacher Learning: Examining Online Teacher Professional Development

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ABSTRACT

Teachers are constantly facing new challenges that influence their teaching practice, like educational reforms, new policies, or working with digital tools (Darling-Hammond, 2016; Haleem et al., 2022). Implementing new curricula and adapting classroom practices are crucial for improving student achievement (Hattie, 2012), but teachers feel overwhelmed when facing these challenges independently (Penuel et al., 2007). Therefore, participating in professional development (PD), where teachers can access knowledge and support, is essential for an effective educational system. Effective PD changes participating teachers' knowledge, attitudes, beliefs, and skills, improving classroom practices and student achievement (Desimone, 2009). Notably, with new technologies, like videoconferencing, social media, or the use of AI, and global evolvements, like the COVID-19 pandemic, the way PD is made available to teachers and the borders of what activities are considered PD are shifting and transforming. There is ample empirical research on the effectiveness of traditional in-person PD, and many theoretical frameworks (Clarke & Hollingsworth, 2002; Desimone, 2009; Desimone & Garet, 2015) explaining its effectiveness. In contrast, there is little research on newer and innovative forms of PD, like online PD (OPD). OPD through websites, online courses, and online communities has become more prevalent due to its numerous advantages over in-person PD. For instance, OPD gives teachers more time flexibility, faster access to personalized information, and reduces participation costs (Dede et al., 2016). Informal OPD on social media and online communities suggests a great potential for immediate answers and low-barrier access to information (Carpenter & Krutka, 2014; Fischer et al., 2019). However, although early studies provided promising results on the effectiveness of participation in OPD, there is no comprehensive review of the existing literature. Consequentially, OPD still must assert itself against more traditional forms since robust empirical evidence remains limited. Evidence on the direct impact of OPD on classroom practice and student achievement is understudied compared to formal in-person PD, making it difficult for educational stakeholders and researchers to make clear recommendations for OPD participation to teachers.

Therefore, this dissertation answered two research questions. Firstly, it answered whether participation in OPD led to changes and improved outcomes at the teacher, classroom practice, and student level (Study 1). After establishing the effectiveness of OPD in general, it answered how participation in informal OPD, and specifically in online communities, impacted and shaped teachers' teaching practices (Study 2 and Study 3).

I proposed a model of how PD can be described within two dimensions: the modality, whether it is delivered in-person or online, and the formality, whether PD and OPD are facilitated in a more formal or informal setting. Each dimension has advantages and might suit specific situations and circumstances. I used innovative and state-of-the-art methods within educational psychology to investigate OPD, focusing on the understudied dimension of informal OPD.

In the first study (*Effects of Online Teacher Professional Development on Teacher, Classroom, and Student Level Outcomes: A Meta-Analysis*), I synthesized findings from 85 quantitative studies investigating the efficacy and effectiveness of OPD. The results indicated medium effects of OPD participation on the teacher (Hedges' $g = 0.66$) and the classroom level (Hedges' $g = 0.59$) and a small effect on the student level (Hedges' $g = 0.21$). This study provides researchers, policymakers, educational stakeholders, and teachers with evidence for OPD's effectiveness and, therefore, encourages them to promote OPD participation.

In the second study (*Examining Laboratory Investigations in Advanced Placement Biology: Teachers' Perceived Challenges and Their Classroom Practice*), I investigated whether teachers increased the number of laboratory investigations and inquiry learning in their classroom practice in response to an educational reform. Furthermore, the influence of formal PD and informal OPD participation on teachers' perceived challenges with the reform and classroom practice was examined. This study uses data from 1,721 biology teachers in the first three years after the Advanced Placement (AP) Biology curriculum reform in the United States. Applying latent growth curve modeling, I examined changes in the challenges teachers perceive concerning laboratory investigations and the number of laboratory investigations they implemented in their instruction. The results showed that perceived challenges related to the reform decreased over time while the number of laboratory investigations increased. Moreover, participation in informal OPD activities was associated with more laboratory investigations implemented in the first year following the AP redesign. The results suggested the importance of providing adequate OPD preceding the implementation of reforms so that teachers can be best prepared for adjusting classroom practices.

In the third study (*Unlocking the Potential of Educational Resources: The Examination of Sharing and Usage Patterns in Educational Online Communities*), I investigated informal OPD and its effect on classroom practices using an innovative approach by analyzing social media user data on X (formerly known as *Twitter*). Drawing on the Theory of Planned Behavior, I examined how teachers in four German hashtag communities share, perceive, and use teaching materials. The results suggested that resources are not shared equally among the communities.

The sentiment of replies to tweets that contain resources was more positive than negative across all communities. Around 1.5 to 3% of the replies to posts sharing resources suggested an intention to implement them into classroom practice. This study advanced educational research by investigating the impact of informal OPD participation on social media in classroom practice. Moreover, it informs educational stakeholders about the possibilities of online communities as a medium for informal OPD and a place to acquire educational resources like teaching materials.

This dissertation provides a comprehensive understanding of the mechanisms and effectiveness of OPD participation. It reveals that OPD activities can have a direct influence on teacher-level outcomes (Study 1), a direct influence on classroom-level outcomes (Study 1, Study 2, Study 3), and an influence on student achievement (Study 1). Investigating the effectiveness of OPD is crucial to establishing its role as an essential opportunity for teacher PD and giving it the same level of credibility as traditional in-person PD. Both educational stakeholders and PD providers have long overlooked the possibility of informal OPD through online communities. Based on the results of this dissertation, I encourage the widespread adoption of OPD, as it offers various advantages for modern society. Therefore, the results of this dissertation push the frontier of teacher learning by investigating innovative forms of OPD.

ZUSAMMENFASSUNG

Lehrkräfte stehen kontinuierlich vor neuen Herausforderungen, die ihre Unterrichtspraxis beeinflussen, wie zum Beispiel Bildungsreformen, politische Entscheidungen, oder die verstärkte Nutzung digitaler Technologien (Darling-Hammond, 2016; Haleem et al., 2022). Die Umsetzung neuer Lehrpläne und die Anpassung von Unterrichtspraktiken sind entscheidend für die Verbesserung der Leistungen von Schüler und Schülerinnen (Hattie, 2012). Allerdings fühlen sich Lehrkräfte oft überfordert, wenn sie sich diesen Herausforderungen allein stellen müssen (Penuel, 2007). Daher ist die Teilnahme an Fortbildungsmaßnahmen, bei denen Lehrkräfte Zugang zu Wissen und Unterstützung erhalten, für ein effektives Bildungssystem unerlässlich.

Empirische Studien belegen, dass die Teilnahme an wirksamen Fortbildungen das Wissen, die Einstellungen, die Überzeugungen und didaktische Fähigkeiten der Lehrkräfte verändern kann, was sich positiv auf die Unterrichtspraxis und die Leistungen der Schüler und Schülerinnen auswirkt (Clarke & Hollingsworth, 2002; Desimone, 2009; Desimone & Garet, 2015). Mit neuen Technologien wie Videokonferenz-Tools, sozialen Medien oder dem Einsatz von künstlicher Intelligenz und globalen Entwicklungen wie der COVID-19-Pandemie verändert sich die Art und Weise, wie Lehrkräften Fortbildungen zur Verfügung gestellt werden, sowie die Definition dessen, was als Fortbildung gilt. Zahlreiche empirische Untersuchungen und theoretische Modelle erklären bereits die Wirksamkeit traditioneller Präsenz-Fortbildungen (Desimone, 2009).

Im Gegensatz dazu gibt es weniger Forschung zu neueren und innovativen Formen der Fortbildungen, wie den Online-Fortbildungen (OFB). OFB über Websites, Online-Kurse und Online-Communities haben sich aufgrund ihrer zahlreichen Vorteile gegenüber Präsenz-Fortbildungen durchgesetzt. So bieten OFB den Lehrkräften beispielsweise mehr zeitliche Flexibilität, schnelleren Zugang zu personalisierten Informationen und geringere Teilnahmekosten (Dede et al., 2016). Informelle OFB über soziale Medien und Online-Communities bietet ein großes Potenzial für zeitnahe Antworten und einen niedrigschwelligen Zugang zu Informationen (Carpenter & Krutka, 2014; Fischer et al., 2019). Doch obwohl zahlreiche Studien vielversprechende Ergebnisse über die Wirksamkeit von OFB-Teilnahmen vorlegen, fehlt es an einer umfassenden Übersicht über die vorhandene Literatur. Folglich muss OFB weiterhin mit traditionellen Präsenz-Fortbildungen konkurrieren, da es nach wie vor an soliden empirischen Belegen mangelt. Darüber hinaus ist die direkte Auswirkung von OFB auf die Unterrichtspraxis und die Leistungen der Schüler und Schülerinnen im Vergleich zu

formellen, Präsenz-Fortbildungen bislang unzureichend untersucht. Dies erschwert es Bildungsakteur:innen und Forscher:innen die Teilnahme an OFB für Lehrkräfte vorbehaltlos zu empfehlen.

In dieser Dissertation wurden zwei Forschungsfragen beantworten. Erstens wurde untersucht, ob die Teilnahme an OFB Veränderungen und Verbesserungen auf Lehrkräfteebene, auf die Unterrichtspraxis und bei Schülern und Schülerinnen bewirkte. (Studie 1). Außerdem wurde der Forschungsfrage nachgegangen, wie sich die Teilnahme an informellem OFB, insbesondere in Online-Communities, auf die Unterrichtspraxis der Lehrkräfte auswirkt (Studie 2 und Studie 3). Dabei wurden innovative und moderne Methoden der pädagogischen Psychologie und Datenanalyse eingesetzt.

Darüber hinaus wurde ein Modell etabliert, mit dem sich Fortbildungen in zwei Dimensionen beschreiben lassen: zum einen die Modalität, also ob sie in Präsenz oder online stattfindet, und zum anderen die Formalität, ob die Fortbildung in einem eher formellen oder informellen Rahmen durchgeführt wird. Jede Dimension hat Vorteile und kann für bestimmte Situationen und Umstände geeigneter sein.

In der ersten Studie (*Effects of Online Teacher Professional Development on Teacher, Classroom, and Student Level Outcomes: A Meta-Analysis*) habe ich die Ergebnisse von 85 quantitativen Studien zusammengefasst, die die Wirksamkeit von OFB untersucht haben. Die Ergebnisse deuten auf mittlere Effekte der OFB-Teilnahme auf Lehrkräfteebene (Hedges‘ $g = 0{,}66$) und auf Unterrichtspraxis (Hedges‘ $g = 0{,}59$) sowie auf einen geringen Effekt auf Schüler- und Schülerinnenebene (Hedges‘ $g = 0{,}21$) hin. Diese Studie liefert Forscher:innen, politischen Entscheidungsträger:innen, Bildungsakteur:innen und Lehrkräften evidenzbasierte Nachweise zur Wirksamkeit von OFB und regt dazu an, das Angebot an OFB für Lehrkräfte weiter auszubauen.

In der zweiten Studie (*Examining Laboratory Investigations in Advanced Placement Biology: Teachers‘ Perceived Challenges and Their Classroom Practice*) untersuchte ich, ob Lehrkräfte die Anzahl der Laboruntersuchungen und des forschenden Lernens in ihrer Unterrichtspraxis als Reaktion auf eine Bildungsreform erhöhten. Darüber hinaus wurde der Einfluss der OFB-Teilnahme auf die von den Lehrkräften wahrgenommenen Herausforderungen der Reform und ihre Unterrichtspraxis untersucht. Diese Studie verwendet Daten von 1721 Biologielehrkräften in den ersten drei Jahren nach der Reform des Advanced Placement Biologie Lehrplans in den Vereinigten Staaten. Mit Hilfe der Modellierung latenter Wachstumskurven untersuchte ich die Veränderungen bei den von den Lehrkräften wahrgenommenen Herausforderungen in Bezug auf die Implementation von

Laboruntersuchungen und die Anzahl der von ihnen im Unterricht durchgeführten Laboruntersuchungen. Die Ergebnisse zeigen, dass die wahrgenommenen Herausforderungen im Zusammenhang mit der Reform im Laufe der Zeit abnahmen, während die Anzahl der Laboruntersuchungen zunahm. Die Teilnahme an OFB im ersten Jahr der Reform konnte mit mehr durchgeführten Laboruntersuchungen in Verbindung gebracht werden. Die Ergebnisse deuten auf die Relevanz hin, vor der Umsetzung von Reformen eine angemessene Fortbildungsstrategie anzubieten, damit die Lehrkräfte optimal auf die Anpassung der Unterrichtspraktiken vorbereitet werden können.

In der dritten Studie (*Unlocking the Potential of Educational Resources: The Examination of Sharing and Usage Patterns in Educational Online Communities*) untersuchte ich informelle OFB-Teilnahme und ihre Auswirkungen auf die Unterrichtspraktiken mit einem innovativen Ansatz durch die Analyse von Social-Media-Nutzerdaten auf X (früher bekannt als „Twitter“). Auf der Grundlage der Theorie des geplanten Verhaltens (Ajzen, 1991) untersuchte ich, wie Lehrkräfte in vier deutschen Online-Communities, die durch die Markierung mit bestimmten Hashtags classifiziert wurden, Unterrichtsmaterialien teilen, wahrnehmen und nutzen. Die Ergebnisse deuten darauf hin, dass Unterrichtsmaterialien in den Communities nicht gleichmäßig geteilt werden. Darüber hinaus ist die emotionale Valenz der Antworten auf Posts, die Unterrichtsmaterialien enthalten, in allen Communities eher positiv als negativ. Etwa 1,5 bis 3% der Antworten auf Posts, in denen Unterrichtsmaterialien geteilt werden, deuten auf die Absicht hin, diese in die Unterrichtspraxis zu implementieren. Diese Studie leisted einen bedeutenden Beitrag zur Bildungsforschung, indem sie die Auswirkungen informeller OFB-Beteiligung über sozialen Medien auf die Unterrichtspraxis untersucht. Darüber hinaus informiert sie Bildungsakteure über die Möglichkeiten von Online-Communities als Medium für informelles Lernen und als Ort, an dem Bildungsressourcen wie Unterrichtsmaterialien erworben werden können.

Zusammenfassend bietet diese Dissertation einen umfassenden Einblick in die Mechanismen und die Wirksamkeit der Teilnahme an Online-Fortbildungen. Es wird aufgezeigt, dass OFB-Aktivitäten einen direkten Einfluss auf der Lehrkräftebene (Studie 1), einen direkten Einfluss auf die Unterrichtspraxis (Studie 1, Studie 2, Studie 3) sowie einen Einfluss auf die Leistungen der Schülerinnen und Schüler (Studie 1) haben können.

Die Untersuchung der Effektivität von OFB ist von entscheidender Bedeutung, um ihre Etablierung als Standard in der Lehrkräftefortbildung voranzutreiben und ihnen die gleiche Glaubwürdigkeit wie traditionellen Präsenz-Fortbildungen zu verleihen. Sowohl Bildungsakteur:innen als auch Anbieter:innen von Fortbildungssmaßnahmen haben die

Potenziale informeller OFB in Online-Communities lange Zeit übersehen. Daher liefern die Ergebnisse dieser Dissertation wertvolle Einblicke und unterstützen eine weit verbreitete Einführung von OFB, die zahlreiche Vorteile für die moderne Gesellschaft bieten. Insgesamt zeigt diese Dissertation, dass die Untersuchung innovativer Formen der Fortbildung von Lehrkräften die bisherigen Grenzen für Lehrkräftefortbildungen erweitert.

CONTENTS

List of Figures

List of Tables

List of Abbreviations

AP	Advanced Placement
APTC	AP teacher community
CBAM	Concerns-Based Adoption Model
CT	Control-treatment design
ER	Educational resources
K-12	Kindergarten to 12th grade
LIWC	Linguistic Inquiry and Word Count
MOOCs	Massive open online courses
NGSS	Next Generation Science Standards
NRCT	Non-randomized treatment-control group design
NWDS	Non-randomized within-subject design
OER	Open Educational Resources
OPD	Online professional development
OR	Odd’s Ratio
PCK	Pedagogical content knowledge
PD	Professional development
PLC	Professional learning community
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RCT	Randomized control-group design
RWDS	Randomized within-subject design
STEM	Science, technology, engineering, and mathematics
TPACK	Technological pedagogical content knowledge
TPB	Theory of planned behavior
TWLZ	Twitterlehrerzimmer
WSD	Within-subject design

1

Introduction and Theoretical Background

1 Introduction and Theoretical Background

Teachers play a crucial role in the educational system. They are the gatekeepers to knowledge and the driving force of implementing curricula mandated by educational reforms. In a meta-analysis of over 800 effect sizes, Hattie's (2012) work states that the average effect of teachers as contributors to students' success is 0.47 standard deviations (*SD*). Teachers show the most influence on their students compared to student factors (0.39 *SD*), home factors (0.31 *SD*), school factors (0.23 *SD*), or curricula (0.45 *SD*). Rivkin et al. (2005) have found similar results in their analysis of panel data of schools, teachers, and students in the United States, which state that teachers matter significantly for students' math and reading achievement. As a result, many studies have been conducted to identify factors contributing to teachers' exemplary professionalism and competencies.

Building upon the importance of teachers, it becomes clear how crucial well-trained teachers are and how much effort must be made to ensure good teacher training (Darling-Hammond, 2016). Teacher training in universities includes practical courses and didactic and pedagogical classes. Time and resources to cover all areas are limited during university training, and teachers cannot be equipped with every skill and knowledge that might be important for their classroom practice. This especially applies to topics that did not exist during their time at the university, like the competent command of virtual reality or artificial intelligence, posing additional challenges and teaching opportunities (Kasneci et al., 2023).

Eacute and Esteve (2000) further name several social, political, and economic challenges of the 20th century that affect teachers. They argue that a system initially designed to teach an elite but shifted to mass education for every child and young person poses numerous challenges to the teacher and student body. In the last decades, the student body has become more heterogeneous due to migration or shifts in socioeconomic standards, and many teachers are not equipped with knowledge on how to handle some of these circumstances in a manner that contributes to effective teaching and student success (Dixon et al., 2014; Pozas & Letzel, 2020). Other social changes include the demand for more pedagogical involvement in their students' lives or the competent access and use of digital media (Lauermann, 2014).

Furthermore, numerous reforms worldwide have initiated and shaped teachers' practice in recent decades, constantly adjusting to new societal demands, too, and focusing on elevating students' cognitive abilities next to their content knowledge (Helsby, 2000). This mission creates additional challenges for teachers, as they must have content knowledge of their subjects and use effective teaching practices that enhance their students' cognitive skills, like reasoning or self-regulation. Therefore, continuous PD helps teachers gain knowledge and skills to develop the teaching skills necessary for the demands of an ever-shifting society and its job market (Darling-Hammond, 2016).

Traditionally, teachers' PD programs are administered in-person in seminar- or workshop-like activities, which are often top-down mandated, making them formal in their approach. The teacher trainer takes on the role of an expert (Borko, 2004). The workshop often encompasses a broad spectrum of topics that the teacher trainer deems relevant. These formats are especially suited for familiarization with educational reform changes, where the aim is to educate as many teachers as possible about the reform content and changes in classroom practices (Guskey, 2000).

Empirical studies and systematic reviews examining the effectiveness of PD participation have generally found positive outcomes for teachers, their classroom practice, and their students' achievement. For example, a review of 28 studies by Kennedy (2016) showed that PD programs focusing on content-specific strategies and active learning opportunities are highly effective for teachers. Another review by Darling-Hammond et al. (2017) emphasized the importance of sustained duration and collective participation in PD activities, noting that programs spanning several weeks to months with collaborative learning opportunities yield significant benefits.

Although formal in-person PD programs are suitable in specific contexts, they have received criticism in our modern, technology-driven world. For instance, the often-mandatory nature of PD participation during the era of educational reforms led to an overflow of programs that were too short and too superficial in their content and were not conceptualized in an evidence-based way to have long-lasting effects (Borko, 2004). Researchers furthermore criticized evaluations of the effectiveness of PD programs as they often show shortcomings with the measurement design, the test instruments, the spatial separation of program features, or the sample size (e.g., Borko, 2004; Bragg et al., 2021; Dede et al., 2008). Moreover, moderators or mediators that influence the effectiveness of PD are often not assessed, which is essential to give insights into enhancing PD effectiveness. To conclude, formal in-person PD can be criticized at different levels, including the structure, the intention, or the delivery (Wei et al., 2009).

In the last decades, educational stakeholders and researchers have gained a new understanding of the complexities of PD, which is now viewed as an ongoing and life-long process rather than just a temporary event. New and innovative forms of PD have begun to emerge, such as online PD (OPD). Teachers can access OPD opportunities that are more personalized, better accessible, cheaper, and more time-convenient than traditional in-person PD (Carpenter & Kurtka, 2014; Dede et al., 2016; Fischer et al., 2019). With the rise of social media, forums, and blogs, teachers can participate in informal OPD, meaning that it is entirely self-organized, driven by their motivation and interest, and not moderated by external teacher trainers (Dede et al., 2009).

In the past decade, ample research on the effectiveness of OPD has emerged, but there are few systematic reviews and no meta-analysis summarizing the corpus of literature. Existing systematic reviews often focus on specific aspects or contexts of OPD. For example, Atmacasoy and Aksu (2018) reviewed studies of blended learning during pre-service education in Turkey. Their findings indicated significant academic gains but were limited to pre-service teachers. Bragg et al. (2021) reviewed eleven studies on OPD design features for in-service teachers. However, they did not include informal OPD formats or social media use or synthesize the effect sizes. Lantz-Andersson et al. (2018) reviewed 52 studies on formal and informal OPD but excluded gray literature and did not synthesize effect sizes. There is a need for meta-analytical studies to evaluate OPD outcomes statistically, considering various moderator variables, to provide broader and more detailed insights into OPD effectiveness. This also means that the better researchers understand PD in all its facets and possibilities, the more effective OPD offers can be made to teachers.

Therefore, in this dissertation, I investigate the effectiveness of OPD using three different aspects to give a comprehensive insight into the possibilities of innovative OPD participation. In the first study, I examined the effectiveness of OPD by summarizing and evaluating research on OPD in the last fifteen years and its effects on the teacher, the classroom practice, and the students' level. In the second study, I analyzed longitudinal data from a nationwide reform in the United States and explored the role of OPD in the context of the reform. With my third study, I zoomed into one of the most innovative forms of informal OPD on social media sites by examining the most significant online education communities on X (formerly known as "Twitter") and how teachers use it to acquire teaching materials.

I propose a model on how PD can be categorized into two dimensions: the formality (formal and informal) and the modality (online and in-person). This dissertation will give new insight into the two dimensions of teacher PD[1] while focusing on the lesser investigated parts,

[1] Throughout this dissertation, I use the terms (teacher) PD when referring to professional development activities in general, which include all forms and dimensions of PD and any activity in which teachers participate to elevate their professional knowledge. When I want to refer to a specific dimension of PD, I make it explicit as either in-person PD (which entails both formal and informal in-person PD) or OPD (also both informal and formal) unless I specifically state the formality. For example, when referring to *informal OPD*, it exclusively entailed professional development activities that are both informal and online. Moreover, the terms in-person and face-to-face are used synonymously.

like OPD. I want to challenge how teacher OPD has traditionally been viewed and give evidence-based insights into innovative forms of OPD, resulting in a more comprehensive view of what teacher PD entails and in which circumstances informal OPD participation can be helpful.

The present dissertation is structured as follows: In Chapter 1, I overview the literature about teachers' participation in PD and OPD and the underlying conceptual frameworks (Chapter 1.2), which state that teachers' PD participation influences three levels: the teachers, their classroom practice, and their students. I then introduce my model of the two dimensions of PD (Chapter 1.3) and review the literature on what is already known about the effectiveness of OPD participation (Chapter 1.4). I then introduce the research questions in Chapter 2 that are answered by the three empirical studies (Chapters 3 to 5). Finally, I discuss the results in Chapter 6, including the strengths and limitations (Chapter 6.2), general implications, and future directions (Chapter 6.3), and end with a final conclusion (Chapter 6.4).

1.1 Teachers' Participation in Professional Development

Professional development is often defined as activities teachers participate in to improve their performance in current or future roles in the school district (Little, 1987). Later, PD was described as ongoing and intentional with systemic learning activities that teachers participate in to enhance their professional knowledge (Guskey, 2000). Craft (2002) described PD as activities that enhance teachers' knowledge beyond their initial training. When the first countries began to centralize the school system and employed strict curricula that defined the content of classes, PD started to get systemized, too (Thair & Treagust, 2003). In the United States, for example, PD became an important endeavor during the post-depression era (Howey & Vaughan, 1983), and PD was mainly considered as an aid to help teachers cover their deficits and not so much to improve good teaching practice further (Guskey, 1986). PD programs were highly structured and were mainly administered by experts in a seminar-like setting, which followed strict goals. Early PD programs were often mandatory in nature and set by law.

Nowadays, PD participation is still mandated in most countries. For example, in OECD countries, except for Denmark, Italy, the Netherlands, and New Zealand, it is mandatory to participate in professional learning, meaning that a certain amount of teacher's work is expected to be dedicated to PD participation (OECD, 2022). In Germany, education is organized by the federal states, meaning that, for example, the federal state of Bavaria and the state of Hamburg can have different educational policies, including the required amount of teacher PD (Eurydice, 2008). Even though in all the states PD participation is mandatory, according to Daschner et al. (2023), only in Bavaria (15 h/year), Bremen (30 h/year), Hamburg (30 h/year), and Berlin (10 h/year), PD participation is quantified and can be controlled (Daschner et al., 2023). Almost all (95%) surveyed teachers in these federal states participated in at least one PD program in 2023. In contrast, only 75% of surveyed teachers in the not-quantified states of North-Rhine Westfalia participated in PD (Daschner et al., 2023).

Similarly, the school system is decentralized in the United States[2], and each state governs its system (US Department of Education, 2008). Teachers have to renew their teaching licenses regularly, and most states mandate ongoing PD participation as a prerequisite for license renewal. School districts typically facilitate these requirements by organizing PD initiatives and providing teachers with opportunities to enhance their educational expertise. Notably, no national guidelines exist for the content and methodology of PD programs. Data

[2] Given that the majority of the data for this dissertation (Study 1 and Study 2) were collected in the United States, this dissertation often referenced and addressed the American educational system in addition to the German educational system.

from the National Center for Education Statistics Schools and Staffing Survey for the academic year 2010–2011 reveals that a significant proportion of teachers –91% of those in elementary education and 78% in secondary education– participated in PD activities tailored to their specific teaching subjects (Goldring et al., 2013). This data shows that most teachers have to make frequent use of PD opportunities and must, therefore, rely on high-quality PD options.

Besides being partially mandatory, other factors can influence PD participation. One factor is the overall motivation for participation, which can vary drastically on an interpersonal level. Some teachers are likelier to seek PD opportunities due to their intrinsic motivation to improve classroom practice, a strong sense of professional responsibility, or a desire for career advancement (Guskey, 2000; Opfer & Pedder, 2011). These teachers often possess a proactive attitude towards learning and self-improvement, driving PD participation. In de Wal et al. (2014) identified profiles of participating teachers based on intrinsic and extrinsic motivation. Extremely motivated teachers engaged voluntarily in PD because they enjoyed it, found it interesting, and valued it as crucial to their goals. Moderately motivated teachers (48% of the sample) were less motivated for PD. The externally regulated motivation type (13% of the sample) was the least motivated for PD participation. They tended to be less likely to engage in ongoing and intense programs and only participated if a PD program was mandated by the school district or principal. Kleickmann et al. (2013) investigated teachers' motivation regarding voluntary PD participation during educational reforms. They found that teachers were more motivated to participate in reform-related PD if they majored in the school subject targeted by the reform and had more experience and a more positive attitude towards formal in-person PD.

Richter et al. (2019) suggest five reasons for PD participation: personal interest, occupational promotion, practical enhancement, social contact, and social stimulation. Other factors suggested by the literature are the personal interest in the topic or the interest in improving their instructional skills (e.g., Appova & Arbaugh, 2018; Gorozidis & Papaioannou, 2014; Kao et al., 2011). Other research has shown that teachers in the early stages of their careers have different PD choices than teachers in later stages (Richter et al., 2011). For example, teachers in the early stages preferred to participate in collaborative and interactive learning, whereas teachers in later stages preferred reading as a PD activity more than teachers in other stages.

Additionally, research has shown that teachers who are already quite skillful and have fewer deficits participate more in PD (e.g., Desimone et al., 2006; Richter et al., 2021; Yoon & Kim, 2022).

Conversely, teachers who may demonstrate a greater need for professional growth, including those struggling with pedagogical challenges or those less confident in their teaching abilities, might be less inclined to engage in PD activities (Hadar & Brody, 2010). Factors contributing to this reluctance include a lack of self-efficacy, perceived irrelevance of PD content, logistical challenges, and the absence of a supportive professional culture. However, a study by Richter et al. (2011) suggested that participation in informal PD and OPD was especially beneficial for teachers with low self-efficacy, motivation, and interest.

In conclusion, the findings from the literature suggest that different teachers have different needs in terms of PD that are linked to intrinsic (e.g., motivation type) and extrinsic factors (e.g., teaching experience, remoteness, and time constraints). Criticisms towards PD programs arise if PD programs and activities do not consider these individual differences by only offering "one-size-fits-all" programs (Borko, 2004). As OPD offers a more personalized PD experience due to easier and more immediate access to input of interest, it shows great potential for a more individualized PD experience. Therefore, it is crucial to offer various PD types that span from formal in-person settings to informal OPD and cater to teachers' individual needs.

1.1.1 Teacher Professional Development during Educational Reforms

Governments often initiate reforms and exam redesign to keep pace with the changing demands of labor markets. Reforms initiated in the last decades have often been informed by scientific research on educational effectiveness, learning, and instruction and by results of extensive studies like the Programme for International Student Assessment (PISA) or the Trends in International Mathematics and Science Study (TIMSS, Breakspear, 2012; OECD, 2013). A recent extensive policy effort in the United States was the introduction of the Next Generation Science Standards (NGSS). The NGSS are science content standards for Kindergarten to 12th grade (K-12) that define the knowledge and skills students need to enhance their understanding and performance in science education. Based on these standards, local educators could design their classroom instruction so that students' interests and science knowledge could be elevated throughout their schooling (NGSS Lead States, 2013). In line with the NGSS reform, biology courses have aligned curricula to these standards. These courses then heavily emphasized laboratory experiments, disciplinary core ideas, crosscutting concepts, and science and engineering practices.

Common denominators of most educational reforms in the last decades are changes in the structure of the classes, the content being taught, and the skills students should acquire through participating in STEM content. For example, the AP Biology, Chemistry, and Physics redesign effort in the United States in the 2010s emphasized an increase in laboratory investigations, the focus on a smaller number of essential core concepts and content, and the increase of inquiry-learning opportunities to increase active learning, critical thinking, and problem-solving skills in students (Pedaste et al., 2012). Several other international reforms in education have been enacted to facilitate these student outcomes in the recent decade, for example, the revision of the National Curriculum Standards in Japan (Yamanaka & Suzuki, 2020) or the changes in the National Framework Curriculum in Finland (Lavonen, 2020). These revised curricula and exams shift from emphasizing memorizing facts to classroom practices that help students acquire conceptual knowledge, problem-solving skills, and reasoning skills.

However, with the initiation of educational reforms, teachers are often concerned about implementing the changes since the new practices can be complex and time-consuming to understand. The Concerns-Based Adaption Model (CBAM) is often used to describe teachers' concerns with implementing innovations, such as reforms (Hall et al., 1973). Concerns are feelings, thoughts, preoccupations, and considerations given to an issue or task and can directly affect one's performance and implementation (Hall, 1976). Crawford et al. (1998) investigated teachers' concerns while implementing a new statewide algebra curriculum. The results of this study suggested the substantial influence of teacher concerns for classroom practice in education reforms. Charalambous and Philippou (2010) investigated teachers' concerns and beliefs about the efficacy of implementing a mathematics curriculum reform focusing on problem-solving. By investigating 151 questionnaires and 53 teacher logs, the results indicated that teachers' efficacy beliefs impacted their task concerns and that teachers' concerns, in turn, influenced their efficacy beliefs.

Furthermore, if teachers struggle with the logistics of reform, they view the reform as a threat to their students and are more inclined to abandon the efforts. Similarly, Atkins and Vasu (2000) found a significant correlation between concerns, computer confidence, and hours of technology training, suggesting that concerns influence instructional practices, which can be improved by providing teachers with adequate training.

Early research during initial reform efforts has already stressed the importance of providing teachers with PD opportunities to help them reflect on and revise their practice in a supportive environment (Bell & Gilbert, 1996; Penuel et al., 2007). It is essential to engage stakeholders, construct sufficient support systems, and provide ongoing PD for teachers to understand the context of the reform (Fuhrman et al., 1988; Romance & Vitale, 2001). If teachers are not trained enough in the new implementation and do not understand the intended changes, they might implement changes in an unintended way (e.g., Karavas-Doukas, 2014;

Sikes, 2014). A study investigating the impact of teacher PD during and after a state-wide science and mathematics reform in the United States has shown that teachers who participated in PD showed a change in attitudes toward inquiry-based teaching strategies. Additionally, their use of inquiry-based instructional practices increased, resulting in sustained achievement gains even over time (Supovitz et al., 2000).

Fishman (2014) investigated how teachers' choice of PD during the AP Biology reform links with students' achievement and found that, although with only small effect sizes, specific patterns of PD participation influenced students' AP Biology exam scores. Similar studies investigating the AP Chemistry and Physics redesigns showed that PD participation, specifically informal OPD participation in online teacher communities, helped teachers align their instructional practice to the curriculum reform (Fischer et al., 2018). Therefore, if reforms aim to improve student learning, adequate teacher training and PD are prerequisites for successful reform implementations.

These results from the literature show the importance of ongoing PD participation during educational reforms, which poses a time of uncertainty for teachers as they experience a top-down mandated shift and disruption of their usual knowledge and classroom practice. By participating in PD, they can understand these changes, adapt to them, and ensure good teaching quality.

1.2 Conceptual Frameworks of Professional Development

In this chapter, I first introduce theoretical models of teacher PD, mostly focusing on conceptual frameworks used to describe the effectiveness of in-person PD. As OPD is a fairly new approach to PD, extensive theories of OPD effectiveness are still lacking in the literature. However, it is important to understand the general framework of teacher PD, like Desimone's (2009) conceptual framework of effective PD participation, which is the most known and implemented conceptual framework. It provides a basis for all forms of PD. Further, I will introduce some first frameworks that focus on OPD. Through the extensive theoretical background, I highlight how this dissertation fits into the current research landscape and what new information the results will bring to the theory and practical implementations of formal and informal OPD.

1.2.1 Theory of Teacher Change

An early theory that explained how PD participation affects teachers and changes in their practice is the theory of teacher change. As Guskey (2000) stated, the theory of teacher change evolved from theorist Karl Lewin, who derived his ideas of teacher change from psychotherapeutic models. It focuses on the specific features of PD that promote short-term change and long-term growth in teacher knowledge and teaching practices. Guskey and Huberman (1995) used these ideas to create models of teacher change that suit experienced teachers better and distinguished between the three levels of outcome: the teacher level, the classroom practice level, and the student level. In these early models, the sequence in which change happened started when teachers participated in PD and implemented classroom changes. If these changes showed signs of success on the student level, only then did teachers' knowledge, beliefs, and attitudes change.

Guskey (1986) further expanded the model but left the changes in student learning in the foreground; he states that changes on this level precede changes in teachers' knowledge and beliefs. Cobb et al. (1990) described a similar approach to Guskey's. However, they emphasized the classroom practice implementation more and included a new facet of PD, where teachers need "cognitive conflict" to help them attempt to modify their classroom practice.

In later studies, Clarke and Hollingsworth (2002) drew the first empirical model for what they coined "teacher professional growth." They understand change in different dimensions: teachers can change as a response to their training or when they adapt their practices to the changed conditions (i.e., change as an adaption). As change is a personal development where teachers "seek to change" to improve their performance or learn new skills, change can also come in the form of systemic reconstruction, where teachers enact the system's policies. Lastly, teachers constantly change through their professional activities. They are learners within their community and continuously adjust their teaching anew. Additionally, in contrast to previous work that viewed PD as a method to fill teachers' deficits, Clarke and Hollingsworth (2002) perceived PD as a complex process involving learning as a form of change.

The theory of teacher change has undergone many iterations, and there is still no consensus about how the different levels are interlinked and on which level change has to occur first for it to penetrate the others. However, what is clear is that the common denominator of these theories is that there are three levels of impact: the teacher, the classroom, and the student level. The outcomes that PD can target vary from level to level. So, what features should PD look like if the goal is to induce any change? This question will be answered in the following subsection (1.2.2).

1.2.2 Features of Effective Professional Development

Early studies have identified special features that make PD effective during educational reforms: PD should engage teachers in pursuing genuine questions and problems and pique their curiosity about the topic strongly enough for a change in their instruction to follow (Little, 1993) and collaborative learning showed some success with teachers who work and learn collectively (Hodgson, 1986; Little, 1993). More generally, Kennedy (1998) stated that the relevance of the content of the PD to the teachers and their teaching is essential. The study found that PD programs that focused solely on teachers' behavior showed a smaller effect on student learning than programs with a stronger focus on providing teachers with new and detailed content knowledge of their subject, curriculum, or concrete learning processes of students. This work prompted other researchers to test the importance of content focus in PD. They found that intensive, sustained, and job-embedded PD focusing on subject content is more likely to lead to improvements (Desimone, 2002; Garet et al., 2001; Yoon et al., 2007).

Loucks-Horsley et al. (2009) describe that in addition to a focus on subject content, designing compelling PD features is necessary and named the direct alignment of PD content with student learning needs as one of the features. Furthermore, PD should be intensive, ongoing, and connected to practice; it should focus on the teaching and learning of academic content, should be collaborative, and fit into school policies and context. Additionally, it should be continuously monitored and evaluated.

In their meta-analysis, Yoon et al., 2007 investigated the effectiveness of various PD features in nine studies that examined a direct link between teachers' PD outcomes and their student's achievements. They found that a duration of 49 hours can elevate their students' achievement by 21 percentile points, labeling the effect as substantively important. However, the authors also argued that there is still a lack of empirical evidence concerning the optimal time duration for participation, and this consensus still has not been found in more recent studies (Postholm, 2012; Sancar et al., 2021).

Other researchers, such as Antoniou and Kyriakides (2013), emphasized the role of teacher characteristics and personality as factors of effective PD participation since characteristics can influence the implementation of new knowledge and skills. According to Kyriakides et al. (2017), the PD process should satisfy teachers' needs while engaging them in a systematic and directed process. Moreover, context-situated and practice-based PD programs have increased teachers' confidence levels and competencies (Ní Ríordáin et al., 2017).

As this subsection (1.2.2) highlights, research has shown that several PD features influence the participating teachers' outcomes and learning gains. However, the most influential study of the effectiveness of teacher PD was published by Laura Desimone in 2009, in which she proposed five core features based on contemporary literature. This framework will be explained in more detail in the subsection (1.2.3).

1.2.3 Desimone's Framework of Effective Professional Development

Desimone (2009) created a conceptual framework for effective participation in PD programs based on literature investigating the effectiveness of certain program features. This framework outlines the mechanisms and outcomes of successful PD participation. The goal of the conceptual framework was to create a blueprint of empirical evidence of PD features so that the quality of PD can be improved. Furthermore, the framework provided information on how the effectiveness of PD can be measured and evaluated. Desimone (2009) defined PD as any profession-related learning experience for teachers. PD can range from formal, structured seminars to everyday informal profession-related conversations with colleagues. Desimone argued that in addition to earlier models of PD (e.g., Little, 1993), it is crucial to incorporate core features of PD that are effective so that they can guide as a measure of effectiveness. Moreover, the core features should provide a foundation to empirically investigate their relative impact and importance and identify variables mediating and moderating PD effects. Based on empirical evidence, which is going to be described in more detail below, Desimone (2009) identified five core features of effective PD: content focus, active learning, coherency, duration, and collective participation.

Studies have indicated that a strong focus on content and subject matter during the PD program is linked to increased teacher knowledge and skills and improves teaching practice (e.g., Desimone, 2002; Garet et al., 2001). PD has a content focus if it provides activities that help teachers learn new or more detailed information related to their subject (Althauser, 2015; Desimone, 2011).

Active learning, as another core feature, happens when teachers are engaged with their materials and can actively reflect on them and construct new insights and knowledge. Active learning can happen while discussing videotaped classroom observations, working on assignments and tasks, and receiving feedback on them, participating in discussions, and reviewing student work (Banilower & Shimkus, 2004; Borko, 2004; Gee & Whaley, 2016; Marsh & Mitchell, 2014).

Coherence as a core feature describes how the PD activity is consistent with previous or other PD, with teachers' knowledge and beliefs, and with their school, district, and state reforms and policies (Desimone, 2011) and the internal coherency of the PD program (Garet et al., 2001; Lindvall & Ryve, 2019; Newmann et al., 2001).

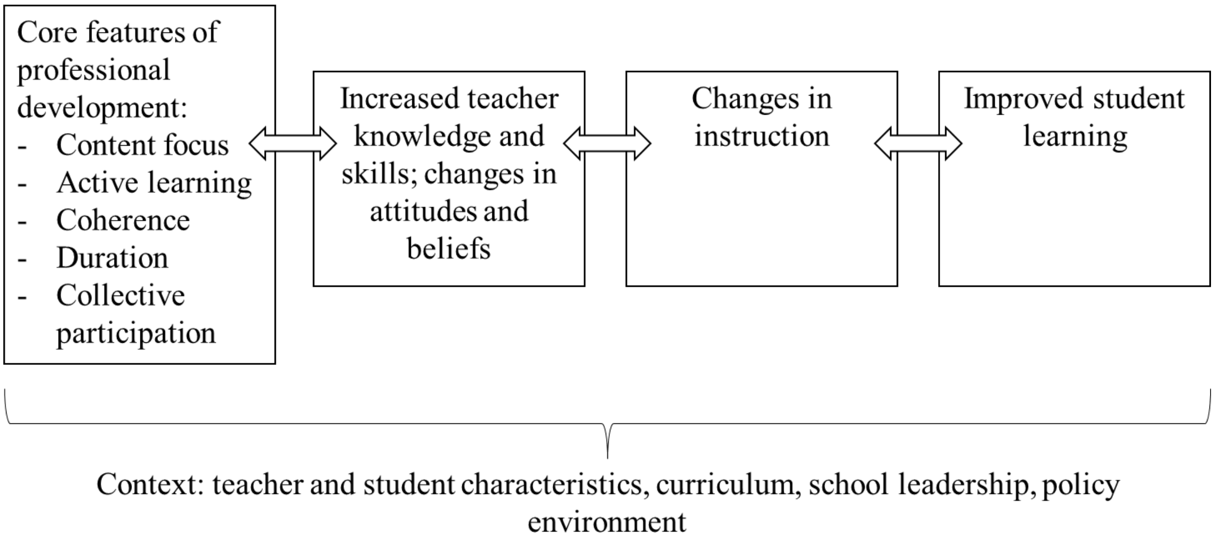
Duration as a core feature remains slightly controversial since there is still no consensus on the impact duration has on the effectiveness of PD. According to Desimone (2011), activities should spread over a semester and include more than 20 hours of contact time. Although research has yet to indicate which program duration is optimal, activities that spread over a semester of more than 40 hours of participation are said to be effective (Borko, 2004).

Finally, collective participation is one factor driving successful PD, facilitated when teachers from a school, grade, departure, or subject exchange their ideas, resources, and concerns with one another, allowing them to learn from each other's experience and forming an interactive learning community (Desimone, 2009; Desimone et al., 2011).

In her conceptual framework (Figure 1), Desimone (2009) proposed a nonrecursive relationship between PD participation, teacher knowledge and beliefs, classroom practice, and student outcomes. However, she stated that a theory of action would likely follow these steps: first, effective PD participation results in an increase in teachers' knowledge and skills; they then adapt this new knowledge to the classroom by changing their classroom practice, resulting in improved instruction. This change in instruction should lead to more effective student learning and higher student achievement.

Figure 1

Conceptual Framework of Effective Teacher Professional Development (adapted from Desimone, 2009)

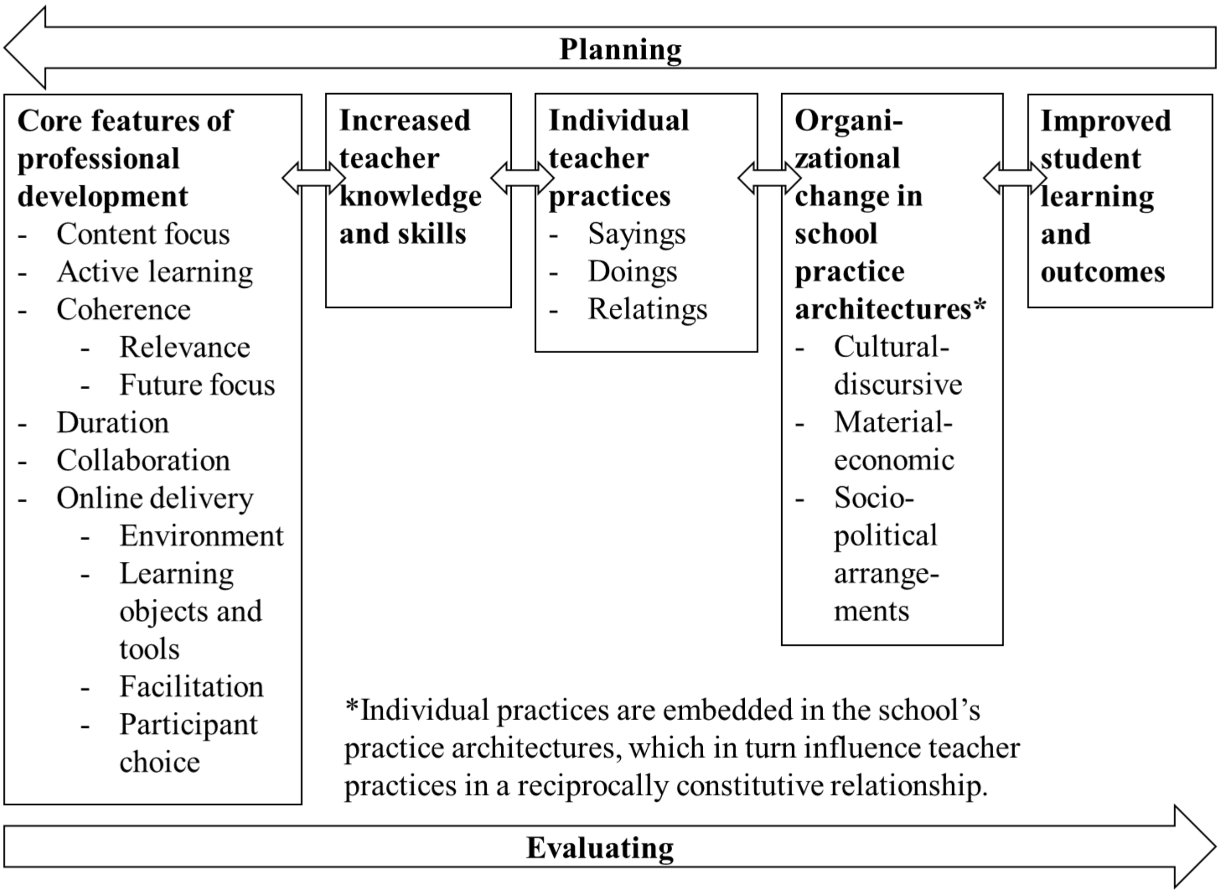


This conceptual framework was revised by Desimone and Garet (2015) by incorporating recent literature and expanding the model. The new framework strongly emphasizes results from randomized controlled trials and the extent of their previous claim by more recent results from the literature. The authors found inter-individual differences between teachers and students in response to PD and that PD is more successful if the content is linked to classroom practice. Furthermore, they recommend that future research should consider the teachers' context and leadership environment as both are crucial for support and implementation. Teachers have unique teaching conditions due to heterogeneous classes that influence what teachers need and want to learn from PD. They suggested that more individualized PD could be offered through a teacher "PD catalog," either online, through workshops, reading materials, or other settings. Teachers should be able to choose between different offers that best suit their individual needs. Another more emphasized point in Desimone and Garet's (2015) revised model was the adaption of PD to urban contexts. In urban contexts, there is often a high principal and student mobility rate and high teacher movements within grades. PD must consider this instability in their timing and workload intensity; for example, more PD programs are needed to train teachers who enter the midst of the school year, and the assessment and evaluation need to take this into account, too. Another point raised was that PD programs should be more adaptive to specific needs and prerequisites based on the variation in teacher responses to the same PD. This variation in outcomes also makes it hard to evaluate and discern specific features of PD.

Quinn et al. (2019) adapted and further developed Desimones' framework for OPD (Figure 2). They added new features specific to the online context, such as the quality and usage of implemented tools and innovative formats. Critical features of OPD include, therefore, a content focus, active learning opportunities, coherence, both in the relevance of the OPD content and of the future focus, opportunities for collaboration between colleagues, and then the online delivery. Furthermore, OPD must account for the environment, learning objects and tools, the facilitation, and the individual choices of the participants. Features like collaborative learning in online communities were especially highlighted. Furthermore, they explain the importance of future-focused PD, which includes informed practices by data derived from governmental data mining. These features allow for a good quality of OPD that increases teachers' knowledge and skills, influences their practices, and relates them to each other. These features are tied to the organizational change in the school practice architectures, like the cultural discourse and the material-economic and socio-political arrangements. All these together lead to or influence student learning and outcomes. The different levels have bidirectional arrows, meaning each level influences the other.

Figure 2

Critical Features of OPD and Conceptual Framework (adapted from Quinn et al., 2019)



1.3 Dimensions of Professional Development

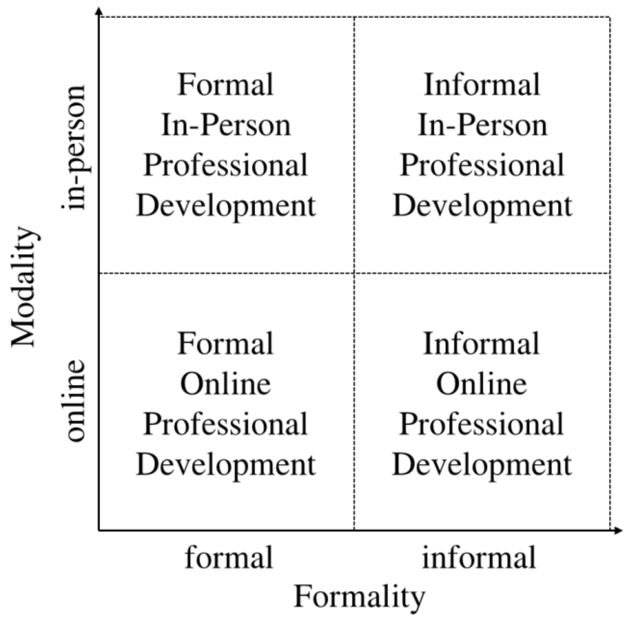
Based on the existing literature, I propose that teacher PD can be characterized along two dimensions (Figure 3). PD can differ in the dimensions of formality and modality. The formality can be either formal or informal. Formal settings refer to top-down mandated workshops, seminars, or courses, with a teacher trainer lecturing about the content and the teacher being perceived as the learner. Informal PD describes self-organized and self-directed PD opportunities that are not externally guided or structured. The dimension of modality refers to in-person (e.g., seminars, classes) or online settings (e.g., online courses, websites, social media).

This 2x2 dimensional design results in four PD formats: formal in-person PD, informal in-person PD, formal OPD, and informal OPD[3]. This distinction is valuable for identifying the features contributing to PD effectiveness within each dimension. Furthermore, research gaps can be revealed by classifying research into the different forms of PD, and a comprehensive understanding of PD and its impact can be developed.

The following subsections explain the four formats in more detail to give a comprehensive overview of their advantages and disadvantages.

Figure 3

The Two Dimensions of Teacher Professional Development with the Resulting Four Formats



[3] Notably, a PD program is not exclusively bound to one format; hybrid/blended PD forms can exist where the PD program incorporates several formats. For example, teachers attend an in-person course but have additional access to an online community. However, since blended PD combines elements of both dimensions and does not constitute a separate dimension, it will not be further explored in this dissertation.

1.3.1 Formal In-Person Professional Development

Most PD programs are traditionally administered top-down in a mandated, in-person, and formal setting. Teachers participate in in-person seminars or workshops with a fixed duration, curriculum, and instructional strategy with an expected outcome. These workshops are delivered in a "top-down" hierarchy with an expert/teacher trainer on the top, and teachers are viewed as learners, receiving input from the expert (Borko, 2004). Formal PD often provides certification or credit upon completion, and sometimes, these certifications are essential for career advancements (Darling-Hammond et al., 2017; Guskey, 2000). The most common challenges with formal in-person PD are that teachers often lack time to participate, do not find all PD topics relevant, and – especially in rural areas – lack access to effective PD due to long journeys (Borko, 2004; Cohen & Hill, 2001; Wei et al., 2009). Formal in-person PD attendance can be costly because teachers have to travel to the event venue, so teachers must consider which program offers the best value for their money. Moreover, due to these constraints, formal in-person PD is often not sustained long enough to change practice effectively (Ingersoll & Strong, 2011). Advantages that teachers often name are the ability to meet their colleagues in person, which could facilitate a sense of community and belonging and foster professional capital and collaboration (Hargreaves & Fullan, 2015; Vangrieken et al., 2017) by giving them the possibility of immediate feedback from peers and teacher trainers (Desimone & Garet, 2015).

1.3.2 Informal In-Person Professional Development

Informal in-person PD occurs continuously as teachers encounter new ideas, challenges, and experiences daily (Kyndt et al., 2014). It happens often in teacher lounges or meetings with colleagues, where teachers spontaneously talk about problems they encounter in their daily lives (Vangrieken et al., 2017). Another more organized but still bottom-up form of informal in-person PD are professional learning communities that involve collaborating and exploring instructional practices with colleagues in ongoing, unsupervised meetings. Informal in-person PD offers several advantages, like real-life and time interaction, such as discussions, allowing for feedback and clarification of problems from peers without having a sense of hierarchy.

However, informal in-person PD is always bound to a specific time and place, sometimes meaning that teachers must travel long distances to attend these meetings, relying on money and other resources (Borko, 2004; Wei et al., 2009).

1.3.3 Formal Online Professional Development

Formal OPD is accessed through the Internet, encompassing several formats, like multimedia websites, online courses, online communities, or list serves. These designs promote self-directed and self-regulated learning, encouraging teachers to actively decide when and which resources to use for learning (Kleiman et al., 2013). One primary form of formal OPD includes self-directed participation through websites. Teachers access materials and resources on websites, watch videos, read texts, and listen to audio files. Online courses are generally carried out by teacher educators, PD providers, or other trained staff (e.g., Cavalluzzo et al., 2005; Fisher et al., 2010; Reeves & Chiang, 2018). Furthermore, online courses are often characterized by a modular design, where input units are sequential and build off each other. In synchronous formal OPD, all participating teachers must be online and participating simultaneously at a specific time. This can happen when courses are taught via video conference tools such as Zoom, MS Teams, or Skype. Formal OPD programs can also be asynchronous, meaning they are neither bound to a particular schedule nor a geographical place, for example, when the formal OPD is offered through multimedia websites. This allows the teachers to work on given material at their own pace within a structured program.

Massive Open Online Courses (MOOCs) have become a popular option for many teachers who seek formal workshops and courses online but want the advantage of asynchronous and personalized participation. MOOCs allow teachers to learn at their own pace and access high-quality courses from renowned institutions without much cost. The offered courses provide teachers with various topics in their area of interest (Jobe et al., 2014; Misra, 2018).

Formal OPD has the advantage of not being bound to a certain place, resulting in reduced costs and the possibility of reaching a wider audience with personalized content and "just-in-time" answers (Fischer et al., 2019; Fütterer et al., 2021). Notably, in studies comparing outcomes for teacher PD through in-person formats versus online formats, no significant differences could be found, indicating that rather than the mode of delivery, other factors, such as duration, content focus, and the possibility of collaborative learning, might be of greater importance (e.g., Matzat, 2013; Powell & Bodur, 2019; Powell et al., 2010). These results and the advantages of online formats over in-person programs suggest that the shift towards formal OPD provides new opportunities and equally good outcomes for teachers if the formal OPD program is of good quality and designed in a way that considers the important core features that make it effective.

1.3.4 Informal Online Professional Development

Teachers usually initiate informal OPD as a voluntary activity and use it primarily to collaborate with colleagues, learn from one another, and share materials and resources (Kyndt et al., 2016; Ramlo, 2012; Recker et al., 2007). What characterizes all these activities is that the teachers are simultaneously the expert and the learner, leading to a higher sense of autonomy and self-efficacy (Little, 2002; Lohman, 2006). In the literature, informal OPD is also known as informal learning, emphasizing its self-directed and organized nature (Avalos, 2011; Richter et al., 2011). Teachers mainly participate in online forums, blogs, and social networking sites like Facebook, X, and Reddit for this form of OPD. Informal OPD is typically self-directed and less structured than formal OPD, which allows for more flexibility and personalization (e.g., Fischer et al., 2019; Lohman, 2006). It usually does not include formal certification or credit, as official sites like universities or accredited PD providers do not provide it. Informal OPD includes diverse learning opportunities like reading articles or books, participating in social media groups, or conversing with colleagues online. Some examples of informal OPD are collaborative discussions with peers, self-study, observations, and reflective practice (de Laat & Schreurs, 2013; Moolenaar, 2012). Informal OPD requires teachers' cognitive and emotional involvement in activities that deepen and extend their professional competence.

Informal OPD is generally more accessible to most teachers, as it can be pursued at their own pace. Another advantage is immediately addressing specific needs or questions as they arise. For example, coaching and mentoring have become an essential and well-investigated mode of informal learning in recent years. In their meta-analysis, Kraft et al. (2018) investigated 60 studies that showed an effect size of 0.49 *SD* for coaching and mentoring on improvements in classroom instruction and a 0.18 *SD* effect size on student achievement, proving that coaching and mentoring are effective due to their personalized, intensive, and sustained nature. They also consider context-specific effects more than one-shot workshops. In their systematic review, (Kyndt et al., 2016) found that collaboration with colleagues, browsing the Internet and social media, and sharing materials and resources were some of the teachers' most commonly identified learning activities.

These materials that teachers find online are free of copyrights and are known as "Open Educational Resources" (OER). Since textbooks and official lesson plans can be outdated, teachers often turn to materials they find on the Internet and have no copyright restrictions so that they can be used, altered, and distributed (Blomgren, 2018; Hylén, 2006; Olivier & Rambow, 2023). Teachers can access OER for their teaching over several repositories, with each country having different popular ones. Lower costs and accessibility are the main reasons teachers use OER for teaching. Research suggested that teachers perceived the quality of OER as satisfactory and comparable to or even better than traditional textbooks (Hilton, 2016; Kimmons, 2015).

Bruguera et al. (2019) found a large increase in studies examining online communities for professional learning between 2013 and 2017, indicating a growth in research interest in this topic. These communities can be found in blogs, forums, or social networking sites, and participation on those platforms has become an everyday activity for many teachers (for review, see Macià & García, 2016).

Studies showed that online teacher communities in microblogging platforms like X (formally known as “Twitter”) are a promising platform for teachers to engage in collective participation (for review, see Bruguera et al., 2019; Greenhow et al., 2018). X is a microblogging platform where users can communicate via limited short text (up to 280 Unicode characters; now paying users can post up to 4,000 characters) or audio/video messages called “posts.” Posts can be referenced to specific hashtags (“#”) and users (by adding an @ in front of the user’s name). Users can communicate through liking, commenting, and reposting (i.e., sharing) other users’ posts, following other users’ content, and sharing it with their followers. Several studies have reported that teachers mainly use X to network, share resources, and collaborate with colleagues for emotional support and to combat isolation (Carpenter & Krutka, 2014; Staudt Willet, 2019; Wesely, 2013).

Participation in X might meet some criteria of high-quality PD as proposed by Desimone (2009), such as collective participation and adequate duration (Fischer et al., 2019; Greenhalgh et al., 2020), since teachers are typically active daily on X (Carpenter & Krutka, 2014; Fischer et al., 2019; Visser et al., 2014). Another common informal OPD activity is participation in online teacher communities. Online communities often exhibit signs of a community of practice (COP), where people frequently interact with each other and learn by sharing and acquiring resources (Fischer et al., 2019; Rosenberg et al., 2020; Wesely, 2013).

The ”just-in-time” nature of informal OPD is also evident in times of uncertainty or the introduction of innovations. Fütterer et al. (2023) investigated how innovations in education, like ChatGPT, are being discussed amongst more than 16,800,00 posts on X in the first two months after the release of ChatGPT. The results showed an incredible increase in the word “ChatGPT”, with more than 100,000 posts per day at the beginning of December 2022 to over 500,000 by the End of January, indicating the rise of awareness and relevancy of ChatGPT. ChatGPT was mostly discussed within the educational X-Sphere, from students’ essay writing and cheating to broader issues like opportunities, limitations, and how to access and use ChatGPT.

The strength of informal OPD lies in the high accessibility, “just-in-time” answers, and access to personalized information, making informal OPD a powerful tool for teacher learning in times of uncertainty, like during educational reforms or other societal shifts.

1.4 Effectiveness of Online Professional Development

In the previous chapters, I highlighted the mechanisms of OPD on teacher change and outcomes on the teacher, classroom, and student levels without going into detail about what these changes might entail and which outcomes can be targeted by OPD. In the following chapter, I will give an overview of the literature that has examined the effects and induced changes of OPD participation on the teacher, the classroom practice, and the student outcome levels.

1.4.1 Effects of Online Professional Development on the Teacher Level

The biggest pool of current literature on the effectiveness of teacher OPD describes outcomes at the teacher level. These outcomes can be divided into two focus areas: a) content knowledge or competencies and skills, such as technological or pedagogical knowledge, and b) attitudes and beliefs necessary for good teaching.

There is a consensus that teachers' understanding and knowledge of their teaching content are linked to their ability to teach it (Shallcross et al., 2002; Wilkins, 2008). Several studies have investigated the influence of OPD to enhance mathematical teachers' content knowledge and found positive outcomes for the content knowledge of participating teachers compared to a control group of teachers (Avineri, 2016; Cady & Rearden, 2009; Dash et al., 2012; Francis-Poscente & Jacobsen, 2013). Carey (2008) investigated middle school algebra teachers' OPD participation in an online course. The course consisted of nine online sessions, peer feedback, and collaborative learning activities. The results showed that participating teachers had higher scores in the posttest in their mathematical understanding and pedagogical beliefs than teachers in the control group. A study by Jiménez and O'Shanahan (2016) investigated 516 Spanish teachers' changes in their knowledge and beliefs on learning to read after attending a web-based seminar. The results suggest improvements in the teachers' knowledge of phonemic awareness, systematic phonics instruction, fluency, and other linguistic and reading qualities.

Pedagogical content knowledge (PCK) is also an essential outcome for OPD to target because it improves classroom practice (Barendsen & Henze, 2019). In a study by Dash et al. (2012), mathematics teachers participated for over 70 hours in an OPD course about fractions, algebraic thinking, and measurements, where teachers also learned instructional and pedagogical strategies. The results show that participating teachers increased their PCK and pedagogical practices.

Other teacher knowledge variables targeted by OPD programs range from teachers' knowledge of specific classroom instruction techniques (Fisher et al., 2010; Herrera, 2012; Hott et al., 2019) to knowledge of working with special needs students or interacting with the students' families in a right way (Boomgard, 2013; Glang et al., 2019; Kim & Morningstar, 2007). The results demonstrate a significant improvement in teachers' knowledge after OPD participation.

Other skills, like specific pedagogical strategies, listening skills, and scaffolding skills, have also been targeted by OPD programs, where teachers successfully acquired and implemented these skills after OPD participation (e.g., Andersen et al., 2011; Cady & Rearden, 2009; Derri et al., 2012).

Furthermore, teachers' beliefs and attitudes, like their self-efficacy of their teaching skills, are another factor contributing to good teaching and are essential to target through OPD programs. Specifically, some studies have shown associations between teachers' self-efficacy and their students' achievement (Mojavez & Poodineh Tami, 2012; Ross et al., 2001), where higher self-efficacy scores of the teachers were correlated with better student achievement. Self-efficacy can also be linked to specific teacher skills. The connection between teachers' technological integration skills and self-efficacy was the subject of some studies (Anderson, 2015; Huai et al., 2006; Marquez et al., 2016). For example, in a study by Anderson (2015), questionnaire data from teachers who participated in X revealed a strong relationship between frequent online collaboration and teachers' sense of self-efficacy for engaging students in learning activities (Anderson, 2015). Similarly, participation in a three-month web-based training helped teachers with their self-efficacy beliefs about inclusive classroom practices (Huai, 2006).

Another line of research investigates teachers' attitudes about their students and how PD participation can facilitate and change them. Notably, researchers have highlighted the importance of teachers' attitudes towards teaching (Boomgard, 2013; Gunter & Reeves, 2017). For example, Monsen et al. (2014) suggested that teachers with more positive attitudes towards including special needs students reported higher student satisfaction and cohesiveness and lower competitiveness and difficulty in their classroom practice than teachers with less positive attitudes.

In conclusion, the literature shows the crucial impact of teachers' participation in OPD on a variety of outcomes, like their knowledge, skills, attitudes, and beliefs.

1.4.2 Effects of Online Professional Development on the Classroom Level

The literature on the direct effects of teachers' participation in OPD on their classroom practice is not as exhaustive as on outcomes at the teacher level. However, some studies have focused on it and investigated this level of OPD impact.

Some skills teachers need for effective teaching are not necessarily part of their formal training. For example, the ability to manage their classrooms has been identified to be a key predictor of student success, with students being more academically engaged (Stronge et al., 2007) and having higher achievements in well-managed classrooms (Back et al., 2016). Acknowledging the importance of this skill, several researchers provided OPD so that teachers could learn about classroom management. For example, Marquez et al. (2016) had teachers participate in the Classroom Management in Action OPD program, where they learned planning, organizing strategies, and responding to problem behavior. The results showed a large effect size on teacher knowledge of classroom management strategies and a small effect on their students' behavior for teachers who participated in the OPD.

Participation in OPD programs that target specific classroom practice strategies is crucial. In smaller studies, like Longoria et al. (2015), teachers were asked how they would rate the instructional practices and teaching skills after participating in writing and utilizing wikis as resources. The teachers reported enhanced teaching skills after frequent participation in wikis.

Participation in the iRAISE intervention program (Jaciw et al., 2016), which targeted science teachers' understanding and practice of their students' ability to understand a variety of scientific texts, showed that teachers reported using a wider variety of text types and opportunities in their classroom practice. Furthermore, they implemented a higher number of instructional comprehension strategies into their practice as compared to teachers who did not receive the iRAISE training. Similarly, a multimedia intervention helped teachers of inclusive science classrooms to significantly implement more vocabulary practices into their teaching (Kennedy et al., 2017).

In a study by Matsumura et al. (2019), 15 teachers participated in an online content-focused coaching program to increase the quality of classroom text discussions. The OPD was a six-week online workshop and included individual, video-based coaching sessions. In surveys, interviews, and analyzed videoed class discussions, the teachers showed positive and significant improvements in classroom practice and students' participation in discussions. A study by Opfer (2018) investigated changes in classroom practice after OPD participation in a workshop for integrating technology and using technology-based literacy tools. Videoed classroom observations suggested that teachers showed sustained changes in their classroom practice and were able to transfer the OPD content knowledge into instructional practice. Furthermore, more studies showed that OPD participation induced changes in classroom practice if the OPD programs were specially designed to target these changes. The programs were effective if teachers were provided with concrete feedback, resources, and opportunities to practice how they could incorporate the learned content into their classroom practice (Patel et al., 2018; Rakap et al., 2014; Schumaker et al., 2010).

In conclusion, literature in this field suggests that specific features of classroom practice can be successfully targeted and improved through teachers' OPD participation.

1.4.3 Effects of Online Professional Development on the Student Level

Literature investigating the direct effects of OPD participation on students' achievement is not as prevalent as literature on the teacher and classroom level. Generally, assessing student outcomes is more difficult, as student learning is multifaceted and strongly influenced by external factors like socioeconomic status, prior knowledge, and the home environment (Blank & Alas, 2009). Since improved student achievement is one of the desired outcomes of teacher OPD, some studies managed to investigate the direct link between teacher OPD participation and their students' achievement, despite the difficulty in assessing outcomes (e.g., Masters et al., 2012; Riel et al., 2017; Schumaker et al., 2010).

For example, Masters et al. (2012) found that students achieved higher scores in vocabulary, reading comprehension, and writing knowledge and practice than students whose teachers did not attend an OPD program for improving teacher knowledge and instructional practices of English language arts.

Fisher et al. (2010) investigated whether the teachers' participation in an OPD program for a concept teaching routine affected their students. The virtual workshop helped teachers advance their knowledge and teaching practices to teach students to process and understand key concepts more effectively and process the information that comes with them. The data from 125 students suggested an improvement in their content knowledge of sociological concepts.

In her dissertation study, Tang (2018) examined the influence of an OPD program on collaborative and peer-tutoring strategies on english learners' reading comprehension, oral reading fluency, and oral expression. The 231 video classroom observations of 77 first-grade teachers showed they successfully incorporated the learned strategies into their practice. Their students also significantly improved their oral expression with a medium to large effect size compared to the control group, which did not receive any treatment.

Strother and Goldenberg (2011) presented the results of an OPD program to enhance biology teachers’ subject content knowledge, pedagogical content knowledge, and use of digital media. The results showed that the 1,100 students in the treatment group had a stronger growth rate across the year for genetics and evolution content knowledge than students in the control group. In a large-scale study, Frumin et al. (2018) investigated the association between teacher participation in the APTC provided by the College Board and changes in their students’ performances on the AP exams. The authors found that students of AP Biology, Chemistry, and Physics teachers who participated in the APTC had higher AP test scores, indicating that informal OPD participation can also be associated with students’ achievement.

In conclusion, while the literature on the direct effects of OPD participation on student achievement is less prevalent than studies focusing on teacher and classroom levels, the existing research demonstrates significant positive impacts.

2

Research Questions

2 Research Questions

The dissertation explores teacher PD in various forms, distinguishing between in-person PD and OPD and formal and informal PD. While there is ample evidence of the effectiveness of in-person PD and its core features, including several meta-analyses and systematic reviews (Desimone et al., 2013; Kennedy, 2016; Kraft et al., 2018; Kyndt et al., 2016; Lindvall & Ryve, 2019; Postholm, 2012; Sims et al., 2021; Yoon et al., 2007), there is not much empirical evidence on the effectiveness of OPD and especially informal OPD. Furthermore, direct links between the participation of informal OPD and classroom practice are still not comprehensive.

The first chapter (Chapter 1.1 Teachers' Participation in Professional Development) overviews the importance of continuous PD participation within different contexts, such as educational reforms or due to intrinsic motivation to better their classroom practices. The chapter emphasizes that PD participation is important to teachers' professional lives and their preparedness to teach in times of uncertainty to ensure an effective educational system.

The second chapter (Chapter 1.2 Conceptual Frameworks of Teacher Professional Development) interweaves theoretical models and empirical studies to present a nuanced understanding of PD. While emphasizing Desimone's (2009) conceptual framework due to its recognition as a significant model discussing effective PD participation mechanisms, I explored other models that build upon Desimone's framework. The exploration offers a profound insight into the evolution of conceptual frameworks for PD, their implementation, and their impact.

The third chapter (Chapter 1.3 Dimensions of Professional Development) introduces my model of how PD can be better categorized with the two dimensions of formality and modality. It also explains the four resulting formats of PD (formal in-person PD, informal in-person PD, formal OPD, informal OPD) in more detail. It provides a literature review on the advantages and disadvantages of each format. From here on, the dissertation focuses solely on the understudied online dimension.

The fourth chapter (Chapter 1.4 Effectiveness of Professional Development) discusses the effects of participation in OPD programs on teachers, classroom practice, and student outcomes. There is substantial evidence that OPD positively affects teachers' knowledge, self-efficacy, and attitudes. However, less evidence is available on the direct impact of OPD on classroom practices and student achievements. The literature also shows some differences in outcomes based on the nature of the OPD, with informal OPD being suggested as more effective in some cases.

In summary, the previous chapters highlighted the importance of PD participation and showed that OPD is still understudied compared to in-person PD. With numerous advantages of OPD and its important role in times of educational reforms and other uncertainties in the form of informal OPD participation, this dissertation, therefore, investigated the following research questions (RQ):

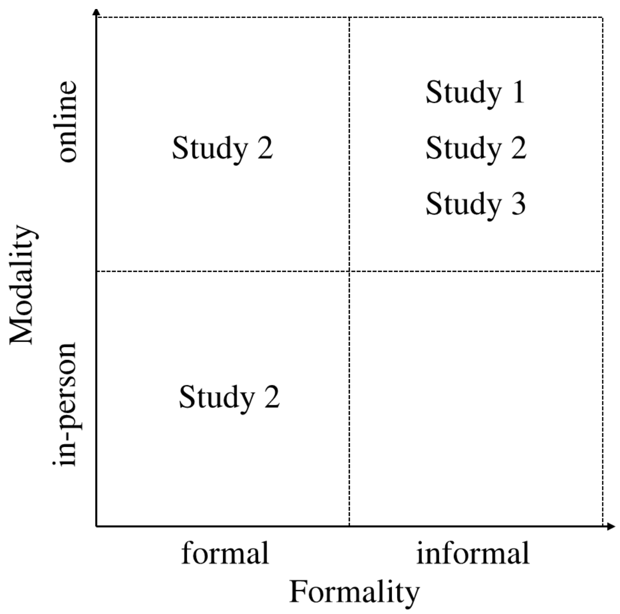
RQ1) How effective is OPD generally for teachers, classroom practice, and student achievement?
RQ2) How can informal OPD participation support teachers with their classroom practice?

A meta-analysis is used to answer the first research question, as this method can give the most comprehensive and statistically robust empirical evidence. Two large-scale approaches are used to answer the second research question by investigating the mechanisms of informal OPD participation in more detail within two different contexts. One of the studies focuses on a top-down mandated educational reform. In contrast, the other study focuses on social media, which is completely voluntary, where informal learning is operationalized as sharing and using online resources.

According to my model of the two dimensions of PD, which differ in modality (online and in-person) and formality (formal and informal), this dissertation covers three PD formats. Each study gives unique insights into the specific dimensions and closes the literature gap, especially for informal and formal OPD. Figure 4 depicts the placement of the three empirical studies in the dimensions model of teacher PD.

Figure 4

Placement of the Studies within the Two Dimensions of Teacher Professional Development



3

Study 1

Morina, F., Fütterer, T., Hübner, N., Zitzmann, S., & Fischer, C. (2023, July 17). *Effects of Online Teacher Professional Development on the Teacher, Classroom, and Student Level: A Meta-Analysis*. https://doi.org/10.31219/osf.io/3yaef. The manuscript was submitted for publication in the Journal of Computer & Education (revise and resubmit) and was published as a pre-print at OSF Preprints.

Abstract

Teachers' professional development is crucial for effective classroom practice. Many teachers have participated in online professional development (OPD) in recent years due to its various advantages. Numerous studies have investigated the effectiveness of OPD either on the teacher, their classroom, or the student level. However, a comprehensive meta-analysis of these studies is missing. This meta-analysis summarizes findings from 85 quantitative studies with a pre-posttest design. The results indicate medium effects of OPD participation on the teacher level (Hedges' $g = 0.66$) and on the classroom level (Hedges' $g = 0.59$) and a small effect on the student level (Hedges' $g = 0.21$). We included Desimones' (2009) core features of effective PD participation as moderators. We found that the core feature of collective participation positively influenced the effect size of the classroom level. Furthermore, we found that studies that employed a control-group design reported significantly lower effect sizes on teacher level outcomes than studies that used a within-subject design. On the student level, studies with asynchronous OPD reported significantly smaller effect sizes than studies with a synchronous OPD format. Our results aim to provide research, policymakers, educational stakeholders, and teachers with the clarity that OPD is effective on several levels and should, therefore, be encouraged.

Keywords. Online Professional Development, In-Service Teacher, Meta-Analysis, Effectiveness

Introduction

Teachers adapt to changing demands in their teaching practice over their careers. These changes can be triggered by many foreseeable and unforeseeable events, such as top-down mandated curriculum reforms, increased implementation of technology in the classrooms, or the COVID-19 pandemic that required a swift transition to emergency distance education. To acquire the skills for tackling these obstacles and to improve their teaching techniques, teachers participate in professional development (PD; e.g., Darling-Hammond, 2009; Desimone et al., 2013).

In recent years, teacher PD has expanded into online spaces, like multimedia websites, online courses, video conferencing, or even more unconventional platforms, such as social networking sites, resulting in a new form of PD: online professional development. (OPD; e.g., Dede et al., 2009; Dede et al., 2016). Research suggests that OPD is just as effective as face-to-face PD for teacher outcomes (e.g., Fisher et al., 2010; Fishman et al., 2013; Masters et al., 2010) and that there is no general pattern of PD associated with student learning outcomes (Hübner et al., 2021) OPD might be particularly promising regarding accessibility, more personalized content, and reduced participation fees (e.g., Fishman et al., 2013; Fischer et al., 2019). However, many teachers have initial concerns or doubts about the effectiveness of OPD, especially if they have no prior experience with it (Powell & Bodur, 2019). For example, Kao and Tsai (2009) found that teachers' perceived usefulness of OPD programs is correlated to their self-efficacy toward the Internet. Because the self-efficacy of teachers can improve after participation in OPD, they should accept these formats more in the future (Gunter & Reeves, 2017).

As PD has partially shifted to online formats in the last decade, literature investigating the effectiveness of OPD has increased. Qualitative research with small sample sizes that focuses on teachers' lived experiences with OPD is quite common (e.g., Powell & Bodur, 2019), but also numerous intervention studies have been conducted to investigate and quantify changes in teacher knowledge (e.g., Gunter & Reeves, 2017; Healy et al., 2019), their classroom practice (e.g., Fisher et al., 2010), or their students' achievement (e.g., Masters et al., 2012). However, even though individual studies might provide insight into specific research and can provide precise estimates of the effects they investigated, the results can often not be generalized. Therefore, this meta-analysis aims to evaluate comprehensive evidence from recent literature that examines the effectiveness of participation in OPD for teachers' knowledge, beliefs, and attitudes, their classroom practice, and their students' achievement. We focused on studies of first to 12th-grade in-service teachers and their students. Furthermore, we include numerous moderators that might influence the effectiveness of the OPD programs. The moderators are based on the quality criteria for effective PD proposed by Desimone (2009): content focus, active learning, coherence, duration, and collective participation, and on study characteristics that might influence effect sizes, such as the study design or publication type.

Our study intends to inform educational stakeholders, researchers, and teachers about the effectiveness of OPD programs to provide a more evidence-based approach towards OPD that might influence the attitudes toward OPD participation and help to promote more OPD in teacher education. Additionally, this meta-analysis provides a comprehensive insight into OPD quality criteria that might explain heterogeneous effects based on theoretical underpinnings that help OPD providers to design their courses accordingly.

Theoretical Background

Affordances of Online Professional Development

OPD is defined as activities that are carried out on online platforms that in-service teachers can participate in to learn about specific topics or skills that are related to their professional knowledge (Elliott, 2017). OPD needs to be accessed through the Internet and can encompass several formats, like multimedia websites, online courses, online communities, or list-serves. One main form includes self-directed OPD participation through websites. Teachers access materials and resources on websites, watch videos, read texts, listen to audio files, and communicate with their colleagues through discussion forums or blogs. This format is characterized by access to multiple media formats (e.g., Derri et al., 2012; Sherman et al., 2008) and is often delivered *asynchronously,* where teachers can complete assignments at their own pace (e.g., Bates et al., 2016; Polly & Martin, 2020). Thus, teachers might have a stronger sense of autonomy as well as self-directed and self-regulated learning (Kleiman et al., 2013), which is beneficial for adult learners (Schraw, 2007). Online courses, in contrast, are characterized by a modular design, where units of input are based on one another and are carried out on specific dates, making them *synchronous* in their delivery. Online courses are generally carried out by teacher educators, OPD providers, or other trained staff (e.g., Cavalluzzo et al., 2005; Fisher et al., 2010; Reeves & Chiang, 2018).

An advantage of OPD is that, unlike face-to-face formats, it is not bound to a place. Peltola et al. (2017) suggested that teachers in remote areas and geographic isolation benefit from OPD because it allows them to attend much cheaper courses (Anderson & Anderson, 2010). Furthermore, teachers that are the only ones teaching a subject in their school benefit from OPD, as it offers them a space to collaborate with teachers from other schools.

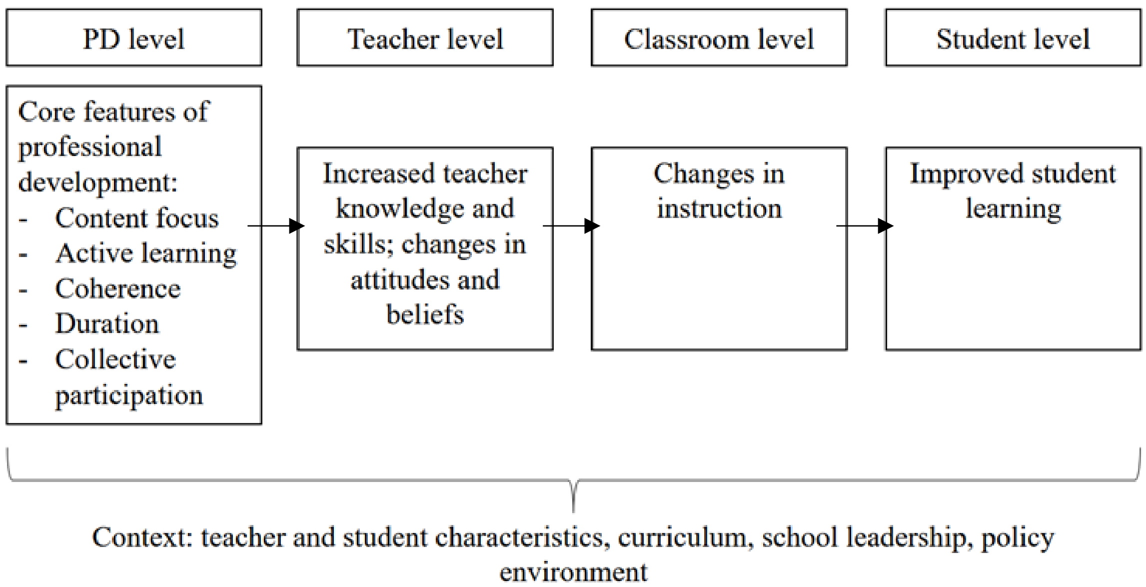
Another advantage of OPD is the flexible accessibility when teachers can access the material with just-as-needed frequency (i.e., how often teachers can access OPD within a specific time frame) and duration (i.e., the total hours teachers spend with OPD). For example, teachers indicated that accessing OPD anytime was essential to them (Parsons et al. 2019). Furthermore, OPD programs give teachers the ability for collective participation with less hierarchical structures. Research suggested that informal exchange in blogs and forums helped teachers learn from one another, share personalized resources, and get support with their individual questions (e.g., Kyndt et al., 2016; Ramlo, 2012; Recker et al., 2007; for review, see Lantz-Andersson et al. 2018).

Effectiveness of Online Professional Development Opportunities

Research shows that participation in OPD or PD can be effective for improvements in teacher knowledge, classroom practice, and student achievement. But how are improvements between these levels interlinked? Desimone (2009) suggested a conceptual framework of the mechanisms and outcomes for effective PD participation. Her conceptual model (Figure 5) states that several core features, such as *content focus*, *active learning*, *coherence*, *duration*, and *collective participation,* determine PD effectiveness.

Figure 5

Conceptual Model of Effective Professional Development



Note. Modeled after Desimone’s (2009) conceptual framework of effective teacher professional development. PD = professional development.

Participation in effective PD should increase teachers' knowledge and teaching skills as well as changes in attitudes and beliefs. The outcome areas, of course, can vary with the PD's objective and the delivered content. Outcomes at the teacher level are typically the main target of many PD programs, therefore affecting teachers immediately (e.g., Cavalluzzo et al., 2005; Gunter & Reeves, 2019; Jiménez et al., 2016). According to Desimone, when teachers experience an increase in their knowledge and skills, they are likely to adapt this new knowledge to the classroom level by changing their classroom practice accordingly, resulting in improved instruction. Improved instruction should lead to more effective student learning and, as a result, higher student achievement. However, these outcomes on the student level might not be as strong as outcomes on the initial teacher level (e.g., Frumin et al., 2018; Kersting et al., 2010). Notably, even though Desimone constructed her conceptual framework based on traditional face-to-face PD, she did not differentiate between PD and OPD formats.

Core Features of Effective Professional Development

As continuous PD is an essential aspect of educational effectiveness, research has tried to examine which features contribute the most to successful PD. Several other publications in the field of effective PD also support Desimone's proposed core features. For example, Darling-Hammond (2009) argued that PD must focus on meaningful content, be embedded in the work of professional learning communities that support collaboration, and should be sustained over time to improve student outcomes. In later publications (Darling-Hammond, 2017), the model was extended by features like active learning opportunities and time for feedback and reflection.

Studies have shown that a strong *content focus* during PD is associated with increased teacher knowledge and skills and improves their teaching practice (Althauser, 2015; Garet et al., 2001). This knowledge can be shared through various materials like videos, podcasts, lectures, or texts.

Another core feature of effective PD is *active learning*, which can take different forms, such as discussing videotaped classroom observations, reflective writing and journaling, working on assignments and tasks, asking questions and receiving feedback on them, and participating in and leading discussions (Borko, 2004; Gee & Whaley, 2016; Marsh & Mitchell, 2014).

Furthermore, *coherency of the program* is vital for effective PD, which describes the consistency of the context in which teacher learning is embedded within prior knowledge, beliefs, and with the school policies and state reforms (e.g., Garet et al., 2001; Newmann et al., 2001; for review, see Lindvall & Ryve, 2019).

Moreover, for PD to be effective, the *duration* of PD must be sufficiently long. There is still a need, however, for a consensus on the length of the duration. Research suggests that a higher frequency of participation in both PD and OPD is beneficial for teacher change (e.g., Bates et al., 2016; Dede et al., 2009; Fischer et al., 2019). Other studies, on the other hand, found that the duration of the OPD depends on what the teachers learn during the OPD since not all content requires a prolonged duration. For example, if an OPD intervention focuses on content knowledge of a topic within a school subject, a shorter duration might be sufficient (e.g., Jiménez et al., 2016; Reeves & Chiang, 2019). In contrast, if the desired outcome of the OPD changes in teaching practice that influence their students, longer duration and more frequent OPD participation is almost essential for the success of the OPD (Magidin de Kramer et al., 2012; Gaumer Erickson, 2012; Jaciw et al., 2016).

Finally, *collective participation* is one aspect driving successful PD, facilitated when teachers from a school, grade, department, or subject network exchange their ideas, resources, and concerns with one another or with educators responsible for PD, allowing them to learn from each other's experiences (Desimone, 2009).

Other studies, like Quinn et al. (2019), extended Desimones' framework to include effective features of OPD. For example, they state that the effectiveness and sustainability of OPD rise when programs include teachers' needs within their own context, the structure of the OPD, and tools.

Associations of OPD Participation with Teacher Variables

Teacher-level outcome variables that PD targets can be divided into two categories: teachers' knowledge, including the knowledge of skills relevant to teaching, and teachers' attitudes and beliefs. Most studies focus on the former. The importance of targeting teacher knowledge lies in the association between teachers' knowledge and their skills to teach and implement the content into their classroom practice (e.g., Shallcross et al., 2002; Wilkins et al., 2008). Previous studies' findings indicate that teachers could improve their content knowledge and knowledge of specific teaching skills when attending OPD programs (e.g., Fisher et al., 2010; Magidin de Kramer et al., 2012; Pape et al., 2015).

Teacher knowledge of pedagogical strategies correlates to the ability to implement them. Various OPD programs have successfully enhanced teachers' pedagogical competencies when working with students (for example, working with students with autism spectrum disorders: Rakap et al., 2014). In summary, many studies demonstrate significant improvements in teachers' knowledge after OPD participation (e.g., Fisher et al., 2010; Healy et al., 2019).

Besides knowledge and skills, teachers' beliefs and attitudes are associated with effective teaching. Specifically, studies have found positive associations between teachers' self-efficacy and their students' achievement (Mojavezi & Tamiz, 2012; Ross et al., 2001). Another line of research investigates teachers' attitudes concerning their students and how OPD participation can facilitate teachers' attitudes (Gosselin, 2010; Gunter & Reeves, 2017; Reeves & Chiang, 2019). Notably, in special education, researchers have highlighted the importance of teachers' attitudes toward teaching and including students with special needs (Monsen et al., 2014).

Associations of OPD Activities with Classroom Practice

Studies indicate that teachers' OPD participation is associated with their classroom practice. Teachers can attend OPD to learn about new classroom practices, like specific teaching strategies, or further develop known teaching strategies. For example, a multimedia intervention helped special education teachers of science classrooms to significantly implement more vocabulary practices into their teaching (Kennedy et al., 2017). Because better classroom practices are associated with better student achievement, OPD targeting classroom practice is highly relevant (for a meta-analytical review, see Schroeder et al., 2007). Alongside classroom practices is the ability to manage classrooms, which is necessary for students' learning as students become more academically engaged (Stronge et al., 2007) and show higher achievement in well-managed classrooms (Back et al., 2016; Freiberg et al., 2009). Literature in this field suggests that specific features of classroom practice can be successfully targeted and improved through the participation of OPD (e.g., Patel et al., 2018; Rakap et al., 2015; Reeves & Chiang, 2019).

Associations of OPD Activities on Student Achievement

As improved student achievement is one of the desired outcomes of teacher OPD, some studies investigated the direct link between teachers' OPD participation and student achievement. An earlier meta-analysis by Yoon et al. (2007), which focused on face-to-face PD, suggested that elementary students showed a moderate effect size in their achievement gain when their teachers participated in PD. However, the authors also stated that due to the high variability between the studies in duration and intensity, it is difficult to discern what makes PD effective for student achievement. Frumin et al. (2018) found that students of AP Biology, Chemistry, and Physics teachers who participated in the AP teacher online community for OPD had higher AP test scores. Fisher et al. (2010) found improvement in students' content knowledge of sociological concepts if their teachers attended an OPD program that targeted their understanding of content knowledge.

Previous Research Reviews on OPD

The literature base of original work investigating the effectiveness of teacher OPD is extensive. However, there are currently only a few systematic reviews and no meta-analysis summarizing solely the literature on OPD across all disciplines and all possible outcomes. Some researchers (Kraft et al., 2018; Lynch et al., 2019) have investigated OPD as a moderator or in relation to a specific context. In their meta-analysis, Lynch et al. (2019) investigated the effectiveness of PD for preK-12 STEM PD and curriculum programs by analyzing 95 experimental and quasi-experimental and included studies from 1994 to 2016. They found an average weighted impact of 0.21 *SD* across all studies, with studies that incorporated an online component having a significantly smaller impact (-0.15 *SD*) on average related to studies without online components. However, most of the online studies in this analysis employed a blended-PD approach and were not solemnly online. Another meta-analysis by Kraft et al. (2018) investigated the effects of teacher coaching programs on teachers' instructional practice and students' academic achievement. The results indicate that there is an effect size of 0.49 *SD* on instruction, and 0.18 *SD* on student achievement and did not find any statistical differences between studies that included online coaching or face-to-face coaching.

Even though some meta-analyses investigated PD with OPD as a moderator (Lynch et al., 2019), systematic reviews of OPD courses are scarce. The few existing systematic reviews about OPD courses focus on individual aspects of OPD or focus on pre-service teacher populations. For example, Atmacasoy and Aksu (2018) investigated blended learning (online and face-to-face components) during the pre-service education of teachers in Turkey. Their review examined 21 articles and ten theses, and a large increase in the pre-service teachers' academic achievement was found. However, the authors only focused on teachers still in training, and the results cannot be generalized to in-service teachers. Pre-service teachers differ from in-service teachers as they do not yet have established classroom routines and might lack the experience to transfer their content knowledge to daily classroom practice (e.g., Kleickmann et al., 2013; Schmeisser et al., 2013).

Furthermore, a recent systematic review by Bragg et al. (2021) focused on specific design features that might contribute to the success of OPD programs for in-service teachers. The study reviewed 11 quantitative and qualitative studies. This overview provided insights into the structural components and design elements of successful OPD programs that target outcomes on the teacher level. However, the review did not incorporate studies with informal

OPD formats or social media utilization. This resulted in a smaller study sample, which does not fully represent the current research landscape. Furthermore, the review did not synthesize the effect sizes of the included studies and, therefore, is in need of a more focused quantitative aspect.

In their review of 52 studies, Lantz-Andersson et al. (2018) investigated teachers' formal and informal OPD participation. The study synthesized literature based on their formality level, the delivery platform, and underlying theoretical models. However, the review did not review gray literature, meaning studies not published in journals, such as dissertation theses, manuscripts, or conference articles. The researchers also did not synthesize the effect sizes of the quantitative studies, thus leaving a gap in the quantitative investigation of associations between teacher OPD and their teaching gains.

Although current reviews provide critical first insights into the overall effectiveness of OPD programs, the existing literature lacks a meta-analytical approach to evaluate the outcomes of OPD effectiveness on a statistical level, pooling the effect sizes and considering several moderator variables incorporated into this study. A meta-analytical perspective on this topic is important because it will allow broader implications across different outcomes and levels and give a chance to view specificities of OPD features and their presumable affordances.

Research Questions

With this meta-analysis, we investigate associations of teachers' participation in formal and informal OPD with outcomes located on three levels, as Desimone (2009) proposed: the teacher, the classroom, and the student level. We aim to synthesize current research and aggregate effect sizes of the respective outcome levels to make quantitative implications of the effects of teachers' OPD participation. We examined three research questions (RQ):

(RQ1) To what extent does teachers' OPD participation affect teachers' knowledge, skills, attitudes, and beliefs?

(RQ2) To what extent does teachers' OPD participation affect classroom practices?

(RQ3) To what extent does teachers' OPD participation affect their students' achievement?

Methods

Data Collection

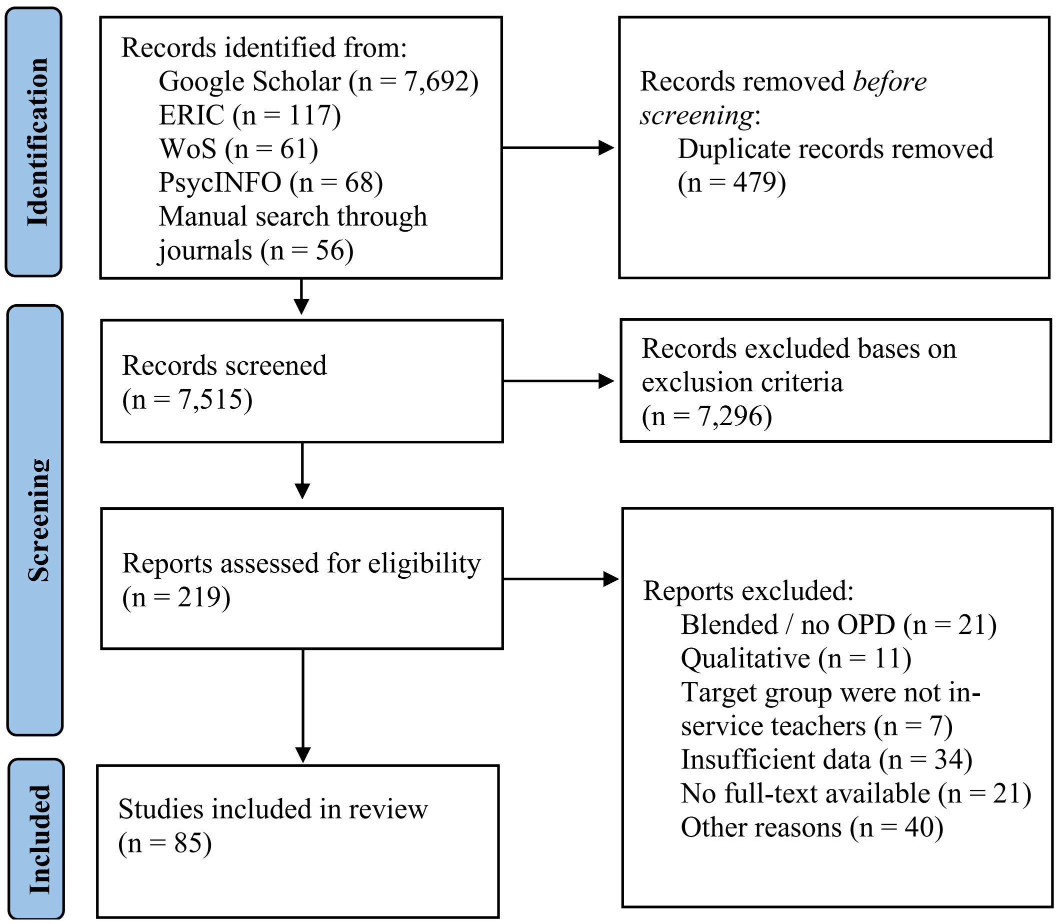
This meta-analysis focused on articles within the last 15 years while not investigating articles published during the COVID-19 pandemic. We chose this timeframe because PD programs during that time were initially conceptualized as face-to-face formats but had to swiftly transition to online formats as a form of emergency education. Whether the programs adhere to the preferred standards for OPD and whether there might be cutbacks in quality has to be further investigated by research which is not yet available today. Therefore, we considered articles from 2005 to 2019 that reflect the scientific landscape before the COVID-19 pandemic. On 15th and 16th September 2020, we conducted a systematic literature search in the online databases Google Scholar, Education Resources Information Center (ERIC), PsycINFO, and Web of Science. We used the search term ("online professional development" AND teacher) AND (effect OR influence OR associated OR impact OR correlation) AND (achievement OR perform OR instruction OR practice OR skill OR attitude OR knowledge) for all databases, except for Google Scholar. For the search in Google Scholar, we had to split the search term into five logically identical parts, as Google Scholar cannot facilitate stacked search terms with more than one operator (see Appendix A). The titles of articles found through Google Scholar were downloaded with custom Python and R scripts. Furthermore, we sent a request for published and unpublished papers to the list-serves of journals that are known to publish literature on teacher professional development. Moreover, we asked fellow researchers via a public tweet if they had unpublished manuscripts that fit our inclusion criteria. The search in all databases yielded 7,717 articles, from which 7,512 remained after duplicates were removed.

Screening

The first author screened the title and abstracts of articles, dissertations, reports, and conference manuscripts and assessed them against the inclusion criteria. Eligible studies were included in the meta-analysis if they met the following inclusion criteria: a) the study was published in English; b) the sample involves K-12 in-service teachers; c) the teachers took part in OPD; d) the OPD intervention targets changes and improvements in either: the teachers level (knowledge, attitudes, skills, beliefs), on the classroom level (teachers classroom practices), and the students level (students' achievement); and e) studies used quantitative research designs. Studies were excluded if they did not fit the inclusion criteria, used only face-to-face activities or a blended PD design, and if teachers were early childhood educators or taught in preschool. Furthermore, the study was excluded if no or not sufficient statistical measures were reported. The articles were marked as either take, toss, or maybe, indicating their status for the next step of the full-text examination. If important information for computing the effect size was missing, the study's authors were contacted. Authors were also contacted if their articles or dissertation's full text was unavailable online. From the initial 7,512 articles, 219 were selected based on the abstract for screening the full text, from which 91 were excluded (Figure 6). From 21 studies that were found eligible based on the abstract, no full text was available; however, after contacting the authors, we had access to three additional studies. From the 219 articles screened, 85 studies from 72 reports were included in the meta-analysis.

Figure 6

Flow Chart of the Study Selection Process



Measures

To collect data from the selected articles, a coding manual and spreadsheet with variables of interest were established (see Table S1, Supplementary Material). Three independent coders were trained for 35 hours. According to PRISMA guidelines, 20% of articles were independently coded by all coders. Inter-rater reliability estimated with Fleiss' Kappa showed satisfactory agreement on the items (κ = 0.59 to 1.00, M = 0.84, with κ >.6 meaning substantial agreement and >.8 almost perfect agreement). For the final dataset, coding differences were resolved through weekly discussions. For the core feature moderators, we coded as conservatively as possible to avoid leaving too much room for interpretation.

We sought intervention outcomes of OPD participation on the teacher, classroom, and student levels. On the teacher level, measures included the sample size, gender (percentage of female teachers in the sample), which grade they were teaching, mean teaching experience (in years), mean OPD duration (in hours), and the time span of the OPD participation (in weeks). Furthermore, outcome variables that were targeted by the OPD (for example, content knowledge, TPACK, technological knowledge, attitudes regarding teaching practices, and self-efficacy) were coded. The outcome variables were made clear by the respective studies that investigated changes through pre-and posttests, and sometimes used validated questionnaires, like the Diagnostic Teacher Assessment of Mathematics and Science (Saderholm et al., 2010) or self-developed questionnaires. In addition, the test instrument and all statistical measures were coded, including the pre-posttest scores of teacher outcomes, reported as means with the respective *SD*, or if not available, the *t*, *F*, *z* scores, or effect sizes.

On the classroom level, outcome variables of the OPD were assessed (for example, the use of concept maps, reading interventions, and classroom management), the test instrument with which the outcomes were assessed, and pre-posttest scores (mean, *SD*, and other test statistics).

On the student level, we assessed the sample size, whether the sample included students with special needs, the test instrument for the student outcomes, and pre-posttest scores (mean, *SD*, and other test statistics).

Moderators

We chose moderators based on the literature on the field of OPD and based on theoretical implications. Leaning on Desimone's proposed core features of effective PD, we identified OPD activities reported by the studies within each core feature and used them as moderator variables. Please refer to the Supplementary Materials (S1) for a more detailed description of the moderators.

For the core feature *content focus,* we identified several OPD activities reported by the included studies associated with *content focus*. Our definition of content focus involves all activities with which OPD content was delivered to the teachers. If part of the OPD entailed watching videos or animations, reading texts, textbooks, or reports, listening to podcasts or other audio files, sharing and acquiring resources, and sharing and acquiring ideas, we coded that the OPD had a content focus, indicated with a "1". If no such activities took place, we coded a "0".

For the moderator *active learning,* we identified the following OPD activities as features: Discussions are part of the active learning process, and they happened between teachers on forums, blogs, or via videoconferencing and were defined as conversations, debates, or exchanges to reach a decision. Furthermore, we defined OPD activities as active learning when they entailed asking questions, which we defined as when teachers were instructed to ask short questions in a Q&A format and not in the form of a discussion. When active learning took place during the OPD, we coded the moderator active learning with a "1" and with a "0" if active learning was not part of the OPD.

For the core feature of *collective participation,* we identified the following OPD activities: networking, which describes activities in which teachers were asked to actively form a sustainable and longer-lasting network with other teachers that might last beyond the OPD program. Networking happens through social media platforms, blogs, and forums. Another OPD activity where teachers experienced collective participation was defined as when teachers collaborated with teacher educators or mentors during the OPD. Typically, they are provided by the organization that also provided the OPD, and collaboration is defined as teachers getting feedback and close supervision from teacher educators or mentors. Furthermore, another feature of networking was giving and receiving emotional support. If these activities were part of the OPD, the moderator collective participation was coded as a "1" and a "0" if not part of the OPD.

For the core feature *coherence* we defined coherence based on Lindvall & Ryve, 2019 who stated that coherence within a PD program can be identified in three ways: a) external coherence, where PD should be coherent with external factors, b) internal coherence, where the program and content of the PD should be aligned with each other, and c) in create coherence, where the PD's content focus is to create more coherence for teachers within their teaching, school context, and curriculum demands. When the OPD showed coherence, we coded the moderator with a "1" and a "0" if the OPD did not show signs of coherence.

We coded the moderator *duration* on a continuous scale based on total hours during the OPD. If a range was reported, we calculated the mean.

Furthermore, we hypothesized that specific study features, like the study design, might influence the reported effect sizes (e.g., Carlson & Schmidt, 1999; Corcoran et al., 2008; Lipsey & Wilson, 1993). We coded four different *study designs*: non-randomized within-subject design (NWDS), randomized within-subject design (RWDS), non-randomized treatment-control group design (NRCT), and randomized treatment-control group designs (RCT). For the moderator analysis, however, we chose to combine the within-subjects design variables and the control-treatment design variables, leading to a dichotomous study design control variable with "0" indicating a within-subject design (WSD) and "1" indicating a treatment-control group design (CT).

We choose to include the *publishing type* as a moderator variable since previous literature has suggested that peer-reviewed and published studies tend to have smaller effect sizes compared to studies that are not peer-reviewed (e.g., Easterbrook et al., 1991; Thornton & Lee, 2000). For this moderator, we used dichotomous coding with “0” indicating studies that were not peer-reviewed (reports and dissertations) and a “1” indicating studies that were peer-reviewed (journal articles and conference papers). Furthermore, we coded the *assessments* of the studies for their outcome variables. We distinguished between self-reported measures (coded as “1”), established questionnaires (coded as “2”), or a mix between both (coded as “3”).

Analytical Methods

The data analysis was conducted with R (R Core Team, 2022) and the R package metafor (Viechtbauer, 2010). We computed Hedges’ *g* (Hedges, 1981) and the effect size variances for each outcome variable for the control-treatment studies using the mean, standard deviation, and sample sizes. We used pre-and posttest scores of the intervention and control groups for calculating the standardized mean difference (*d*) and the sampling variance of *d* (Var[d]; Formula 1).

$$d = ((\bar{x}1 - \bar{x}2))/sp, \qquad (1)$$

$$sp = \surd(((n1-1)\ \llbracket sd1 \rrbracket \text{^}(2) + (n2-1)\ \llbracket sd2 \rrbracket \text{^}2)/(n1+n2-2))$$

$$Var[d] \approx (1/n\_1)/n\_1 + 1/n\_2 + d\text{^}2/(2(n_1 + n\_2))$$

where $x1$ denotes the intervention group’s mean, $x2$ denotes the control group’s mean, and sp denotes the pooled standard deviation for both groups. For the sampling variance, we needed the sample size of the intervention group (n_1) and the sample size of the control group (n_2).

When pretest scores were unavailable, we calculated the effect sizes based on the between-group differences in posttest scores. In within-subject design studies, we calculated the difference between pre-and posttest scores, resulting in the standardized mean change (*dr*; Formula 2).

$$dr = (\bar{x}2 - \bar{x}1)/s1, \qquad (2)$$

$$Var\,[dr] \approx 2\,(1-r)/n + ((\llbracket dr \rrbracket \text{^}(2)))/2n$$

where the standardized mean change was computed by extracting the pretest mean 1 from the posttest mean 2 and dividing it by the pretest standard deviation $s1$. The sampling variance included the sample size n and the correlation coefficient r of the pre-and posttest scores.

If studies did not report means or standard deviations, we calculated the effect sizes based on other available statistical information (e.g., *t, F*, or *p* values) and the sample size. For this process, we used various resources, like the website *psychometrica.com* (Lenhard & Lenhard, 2016), which has automated effect size calculators. Additionally, we used the *Practical Meta-Analysis Effect Size Calculator* (Wilson, 2022) and the *Doing Meta Analysis in R Guide* (Harrer et al., 2021). To calculate the sampling variance for the standardized mean change, the pre-posttest correlation *r* was needed. For studies that reported *r* or data to calculate *r*, we inserted the *r* values into the formula for estimating the sampling variance (Formula 2). For studies that did not report sufficient data, we calculated the mean *r* of the other studies and used this value as a proxy (the formula to calculate *r* can be found in Appendix B).

For each outcome level, a meta-analysis of all effect sizes within the level was performed using the respective SMD and SMC values. Since most studies reported more than one effect size, we used a random effects model with the study ID as a grouping variable. We interpreted the effect sizes based on Hedges' *g* (1981), with $g = 0.8$ as a large effect size, $g = 0.5$ as a medium effect size, and $g = 0.2$ as a small effect size.

Moderator Analyses

To test for variations in effect sizes between studies that are due to a moderator, we conducted a moderator analysis for each moderator using meta-regression.

Heterogeneity Analysis

A homogeneity analysis was conducted with the pooled effect sizes for each level, using Cochran's Q statistic and the I^2 Index. As a more recent approach to testing heterogeneity in meta-analyses, the I^2 Index estimates the percentage of variability in results across studies due to the true difference and not due to chance (Higgins et al., 2003). Furthermore, we reported the RVE-based τ^2, representing an absolute measure of between-studies variability (Schwarzer, 2022; von Hippel, 2015). For the interpretation of the I^2 index, we used the thresholds suggested by Higgins et al. (2003), with 25% for low heterogeneity, 50% for medium, and 75% for high heterogeneity.

Results

5.1 General Characteristics of Included Studies

Eighty-five studies were eligible for the final sample. The studies provided 251 effect sizes. From the 85 studies, 73 reported outcome measures on the teacher level (186 effect sizes), 15 studies reported outcomes on the classroom level (32 effect sizes), and 15 reported outcomes on the student level (33 effect sizes). Overall, 60 studies employed a within-subject design with a pre-and posttest, and 25 used an intervention-control group design. Sample sizes for teachers ranged from 8 to 3,328 (M = 538, SD = 781) and for students from 41 to 3,448 (M = 1,257, SD = 1,041).

Of the studies included, 34 were not peer-reviewed, whereas 51 were. Out of the 85 studies, 80 were conducted or used data from the United States. Most studies were published in 2015 (13.75%) and 2010 (12.5%). Most studies used online courses as the platform for OPD (57.5%), while 21.25% used multimedia websites, 7.5% used online communities, and 13.75% used other platforms. The final sample of included reports can be found in Table 1 (for a comprehensive overview of all included studies, see Table S2, Supplementary Material).

Table 1

Final Reports Sample

Reports	**Outcome Level**
Adada, N. N. (2007). The role of technology in teachers' professional development	T
Ahuna, A. (2014). Just in Time lotus notes support	T
Anderson A., Strother, S., Goldenberg, L., Ferguson, C., & Pasquale, M. (2011). Teacher digital media use following an online professional development course	T
Anderson, B. J. (2015). Professional learning networks, teacher beliefs and practices	T
Avineri, T. A. (2016). Effectiveness of a mathematics education massive open online course as a professional development opportunity for educators	T
Beffa-Negrini, P. A., Cohen, N. L., Laus, M. J., & McLandsborough, L. A. (2007). Development and evaluation of an online, inquiry-based food safety education program for secondary teachers and their students	T
Boland, W. K. (2019). Professional developments' impact on technology use by K-6 educators in a Chinese context: A mixed methods study	T
Boomgard, M. C. (2013). Changes in perceived teacher self-efficacy and burnout as a result of facilitated discussion and self-reflection in an online course to prepare teachers to work with students with autism	T
Byers, A. S. (2010). Examining learner-content interaction importance and efficacy in online, self-directed electronic professional development in science for elementary educators in grades three–six	T
Cady, J., & Rearden, K. (2009). Delivering online professional development in mathematics to rural educators	T
Cain, L. L. (2015). A study of modular professional learning and mentoring and its impact on teacher effectiveness	T
Carey, R., Kleiman, G., Russell, M., Venable, J. D., & Louie, J. (2008). Online courses for math teachers: Comparing self-paced and facilitated cohort approaches	T
Cavalluzzo, L., Lopez, D., Ross, J., & Larson, M. (2005). A study of the effectiveness and cost of AEL's online professional development program in reading in Tennessee	T
Dash, S., Magidin de Kramer, R., O'Dwyer, L. M., Masters, J., & Russell, M. (2012). Impact of online professional development or teacher quality and student achievement in fifth grade mathematics	T, S
Derri, V., Emmanouilidou, K., Antoniou P., & Chatzaraki, V. (2012). Distance versus face-to-face professional development environment: Physical educators' knowledge acquisition on student evaluation	T

Fisher, J. B., Schumaker, J. B., Culbertson, J., & Deshler, D. D. (2010). Effects of a computerized professional development program on teacher and student outcomes	T, C, S
Frumin, K., Dede, C., Fischer, C., Foster, B., Lawrenz, F., Eisenkraft, A., Fishman, B., Jurist Levy, A. & McCoy, A. (2018). Adapting to large-scale changes in Advanced Placement Biology, Chemistry, and Physics: The impact of online teacher communities	S
Gallagher, D. K. (2007). Learning styles, self-efficacy, and satisfaction with online learning: Is online learning for everyone?	T
Gaumer Erickson, A. S. G., Noonan, P. M., & Mccall, Z. (2012). Effectiveness of online professional development for rural special educators	T
Glang, A. E., McCart, M., Slocumb, J., Gau, J. M., Davies, S. C., Gomez, D., & Beck, L. (2019). Preliminary efficacy of online traumatic brain injury professional development for educators: an exploratory randomized clinical trial	T
Gosselin, D. C., Thomas, J., Redmond, A., Larson-Miller, C., Yendra, S., Bonnstetter, R. J., & Slater, T. F. (2010). Laboratory earth: A model of online K-12 teacher coursework	T
Gunter, G. A., & Reeves, J. L. (2017). Online professional development embedded with mobile learning: An examination of teachers' attitudes, engagement and dispositions	T
Hawkins, S. T. (2019). The effect of professional development on teacher knowledge of concussions and classroom support of concussed students	T
Healy, S., Block, M., & Kelly, L. (2019). The impact of online professional development on physical educators' knowledge and implementation of peer tutoring	T
Heck, D. J., Plumley, C. L., Stylianou, D. A., Smith, A. A., & Moffett, G. (2019). Scaling up innovative learning in mathematics: Exploring the effect of different professional development approaches on teacher knowledge, beliefs, and instructional practice	T
Herrera, K. (2013). Evaluating the effect of an online job-embedded professional development program on elementary teachers' use of arts integrated approaches to learning in a south Texas school district	T
Hott, B. L., Raymond, L., & Hightower, H. (2019). Project DREAM Year 2: Validation and pilot of video models to enhance rural east Texas Algebra teachers' knowledge and use of evidence-based strategies	T
Huai, N., Braden, J. P., White, J. L., & Elliott, S. N. (2006). Effect of an internet-based professional development program on teachers' assessment literacy for all students	T
Iizuka, C. A. (2019). Reaching out for people in need: Promotion of emotional resilience for children in disadvantaged communities	S
Itle-Clark, S. (2013). In-service teachers' understanding and teaching of humane education before and after a standards-based intervention	T
Jaciw, A. P., Schellinger, A. M., Lin, L., Zacamy, J., & Toby, M. (2016). Effectiveness of internet-based reading apprenticeship Improving science education (iRAISE)	T, C, S

Jiménez, J. E., & O'Shanahan, I. (2016). Effects of web-based training on Spanish pre-service and in-service teacher knowledge and implicit beliefs on learning to read	T
Jiménez, B. A., Mims, P. J., & Baker, J. (2016). The effects of an online data-based decision professional development for in-service teachers of students with significant disability	T
Kim, K. H., & Morningstar, M. E. (2007). Enhancing secondary special education teachers' knowledge and competencies in working with culturally and linguistically diverse families through online training	T
Kisicki, T., Blair, H., & Nelson, B. (2009). Do teachers enrolled in an online science course learn more when participating in discussion forums?	T
Kowalski, S. M., Stennett, B., Bloom, M., & Askinas, K. (n.d.). Investigation of video-based multidisciplinary online professional development for inservice high school science teachers	T, S
Lauer, P. A., Stoutemyer, K. L., & Van Buhler, R. J. (2005). The McREL rural technology initiative: Research and evaluation study	T
Long, C. L. S. (2015). The impact of asynchronous online course design for professional development on science-teacher self-efficacy	T
Longoria, L., Alobud, O., Black, H. & Olfman, L. (2015). Educator development as predicted by the use of wikis in an e-learning environment	C
Machado, C., & Laverick, D. (2015). Technology integration in K-12 classrooms: The impact of graduate coursework on teachers' knowledge and practice	T
Magidin de Kramer, R., Masters, J., O'Dwyer, L. M., Dash, S., & Russell, M. (2012). Relationship of online teacher professional development to seventh-grade teachers' and students' knowledge and practices in English language arts	T, C, S
Marquez, B., Vincent, C., Marquez, J., Pennefather, J., Smolkowski, K., & Sprague, J. (2016). Opportunities and challenges in training elementary school teachers in classroom management: Initial results from classroom management in action, an online professional development program	T, S
Masters, J., Magidin deKramer, R., O'Dwyer, L. M., Dash, S., Russell, M. (2010). The effects of online professional development on fourth grade English language arts teachers' knowledge and instructional practices	T
Masters, J., Magidin de Kramer, R., O'Dwyer, L., Dash, S., & Russell, M. (2012). The effects of online teacher professional development on fourth grade students' knowledge and practices in English language arts	S
McAleer, D., & Bangert, A. (2011). Professional growth through online mentoring: A study of mathematics mentor teachers	T
McGlothlin, C. D. (2014). Evaluation of HQT online courses: Growth of participants technology, pedagogy and content knowledge (TPACK)	T
Matsumura, L. C., Correnti, R., Walsh, M., Bickel, D. D., & Zook-Howell, D. (2019). Online content-focused coaching to improve classroom discussion quality	C
Mohamadi Zenouzagh, Z. (2019). The effect of online summative and formative teacher assessment on teacher competencies	T
Nelson, A. (2017). Blended professional development: Toward a data-informed model of instruction	T

Opfer, T., & Sprague, D. (2018). Teacher participation in online professional development: Exploring academic year classroom impacts	T, C
Pape, S. J., Prosser, S. K., Griffin, C. C., Dana, N. F., Algina, J., & Bae, J. (2015). Prime online: Developing grades 3-5 teachers' content knowledge for teaching mathematics in an online professional development program	T
Patel, D., Wei, X., Laguarda, K., Stites, R., Cheever, H., & Goetz, H. (2018). Evaluation of education connections: Supporting teachers with standards-based instruction for English learners in mainstream classrooms	T,C
Rakap, S., Jones, H. A., & Emery, A. K. (2015). Evaluation of a web-based professional development program (Project ACE) for teachers of children with autism spectrum disorders	T, C
Reeves, T. D., & Chiang, J. L. (2019). Effects of an asynchronous online data literacy intervention on pre-service and in-service educators' beliefs, self-efficacy, and practices	T, C
Reeves, T. D., & Li, Z. (2012). Teachers' technological readiness for online professional development: evidence from the US e-Learning for Educators initiative	T
Riel, J., Lawless, K. A., Brown, S. W., & Lynn, L. J. (2015). Teacher participation in ongoing online professional development to support curriculum implementation: Effects of the GlobalEd 2 PD program on student affective learning outcomes	S
Riel, J., Lawless, K., & Brown, S. (2017). Timing and spacing of work as predictors of confidence in self-paced, online teacher professional development	T
Rose, M. A. (2010). EnviroTech: Enhancing environmental literacy and technology assessment skills	T
Rose, M. A. (2012). EnviroTech: Student outcomes of an interdisciplinary project that linked technology and environment	S
Russell, M., Kleiman, G., Carey, R., & Douglas, J. (2009). Comparing self-paced and cohort-based online courses for teachers	T
Saldaña, R. (2015). Mobile professional development: Taxonomic levels of learning on teachers' TPACK perceptions and acquisition of technology competencies	T
Sankar, L., & Sankar, C. S. (2010). Comparing the effectiveness of face-to-face and online training on teacher knowledge and confidence	T
Schumaker, J. B., Fisher, J. B., & Walsh, L. D. (2010). The effects of a computerized professional development program on teachers and students with and without disabilities in secondary general education classes	T, S, C
Sherman, G., Byers, A., & Rapp, S. (2008). Evaluation of online, on-demand science professional development material involving two different implementation models	T
Silverman, (2011). Supporting the development of mathematical knowledge for teaching through online asynchronous collaboration	T
Stansberry, S., & Kymes, A. (2005). Tech4u: Increasing teachers' technology literacy through an online professional development community	T
Strother, S., & Goldenberg, L. B. (2011). Examining the student impact following an online professional development course for high school biology teachers	S

Tang, S. (2018). Examining the impact of virtual professional development and teachers' use of the cooperative/collaborative/peer-tutoring strategies on English learners' reading comprehension, oral reading fluency, and oral expression	T, S
Taysever, G. J. (2016). The effects of online professional development on teacher behavior and perceptions of science, technology, engineering, art and math teaching efficacy	T
Uzoff, P. P. (2014). Virtual school teacher's science efficacy beliefs: The effects of community of practice on science-teaching efficacy beliefs	T
Ward, S. (2015). The impact of self-efficacy and professional development on implementation of web 2.0 tools in elementary classrooms	T
Yoo, J. H. (2016). The effect of professional development on teacher efficacy and teachers' self-analysis of their efficacy change	T

Notes. T = teacher level, C = classroom level, S = student level

Main Findings of OPD Effectiveness

The main effect size for all teacher level outcomes yielded an overall medium effect size (Hedges' g = 0.66, SE = 0.09, 95% CI [0.50, 0.81], p < .001) with a heterogeneity I^2 of 99.35% (τ^2 = 0.36, SE = 0.05; see Table 2).

Table 2

Main Results of the Meta-Analysis

Level	k	g (SE)	p-value	95% CI	I^2 (p-value)
Teacher	186	0.656 (0.079)	<.001	[0.502 – 0.811]	99.35% (<.001)
Classroom	32	0.592 (0.128)	<.001	[0.340 – 0.843]	88.96% (<.001)
Student	33	0.205 (0.047)	<.001	[0.113 – 0.298]	99.29% (<.001)

Note. k = number of effect sizes, g = Hedges' g, CI = confidence interval, I^2 = Estimate of the percentage of variability in results across studies.

As expected, the heterogeneity between the studies was high due to the differences in the targeted outcomes of the OPD programs. Therefore, we split the effect sizes into effect sizes of outcomes that target teacher knowledge, and outcomes that target changes in teachers' attitudes and beliefs. The effect size of teacher knowledge outcomes is high (k = 136, Hedges' g = 0.76, SE = 0.1, 95% CI [0.57, 0.94], p < .001), with a high heterogeneity (I^2 = 98.9%, τ^2 = 0.37, SE = 0.06), and for teachers' attitudes and beliefs a slightly smaller effect size, but still high (k = 49, Hedges' g = 0.55, SE = 0.11, 95% CI [0.34, 0.76], p < .001), with a high heterogeneity (I^2 = 99.53%, τ^2 = 0.28, SE = 0.07).

The main effect size for all classroom-level outcomes yielded a medium effect size (Hedges' g = 0.59, SE = 0.13, 95% CI [0.34, 0.84], p <.001) with a heterogeneity I^2 of 88.96% (τ^2 = 0.068, SE = 0.04). The main effect size for all student-level outcomes yielded a small effect size (Hedges' g = 0.21, SE = 0.05, 95% CI [0.11, 0.3], p < .001) with a heterogeneity I^2 of 99.29% (τ^2 = 0.02, SE = 0.01).

Teacher Level

On the teacher level, OPD targets outcome measures including knowledge about classroom practice strategies (31.1%), content knowledge of subjects (22%), teaches' attitudes and beliefs (17%), teachers' self-efficacy (14.1%), technological knowledge, pedagogical content knowledge, or TPACK (6.8%), knowledge about student's assessments (2.8%) or other outcomes (6.2%; a complete list and description can be found in Table S2, Supplementary Materials). Figure 7 depicts the forest plot of all studies with teacher level variable outcomes. Only the moderator *study design* had a significant impact on the effect size on the teacher level indicating that control-group design studies showed significant lower effect sizes (k = 186,

$n = 46$, $\beta = -0.35$, $SE = 0.17$, 95% CI [–0.678, –0.012], $p = .042$) than studies with a within-subject design (see Table 3).

Figure 7

Forest Plot of Effect Sizes on the Teacher Level. Notes. SMD = standardized mean difference (Hedges' g), CI = confidence interval

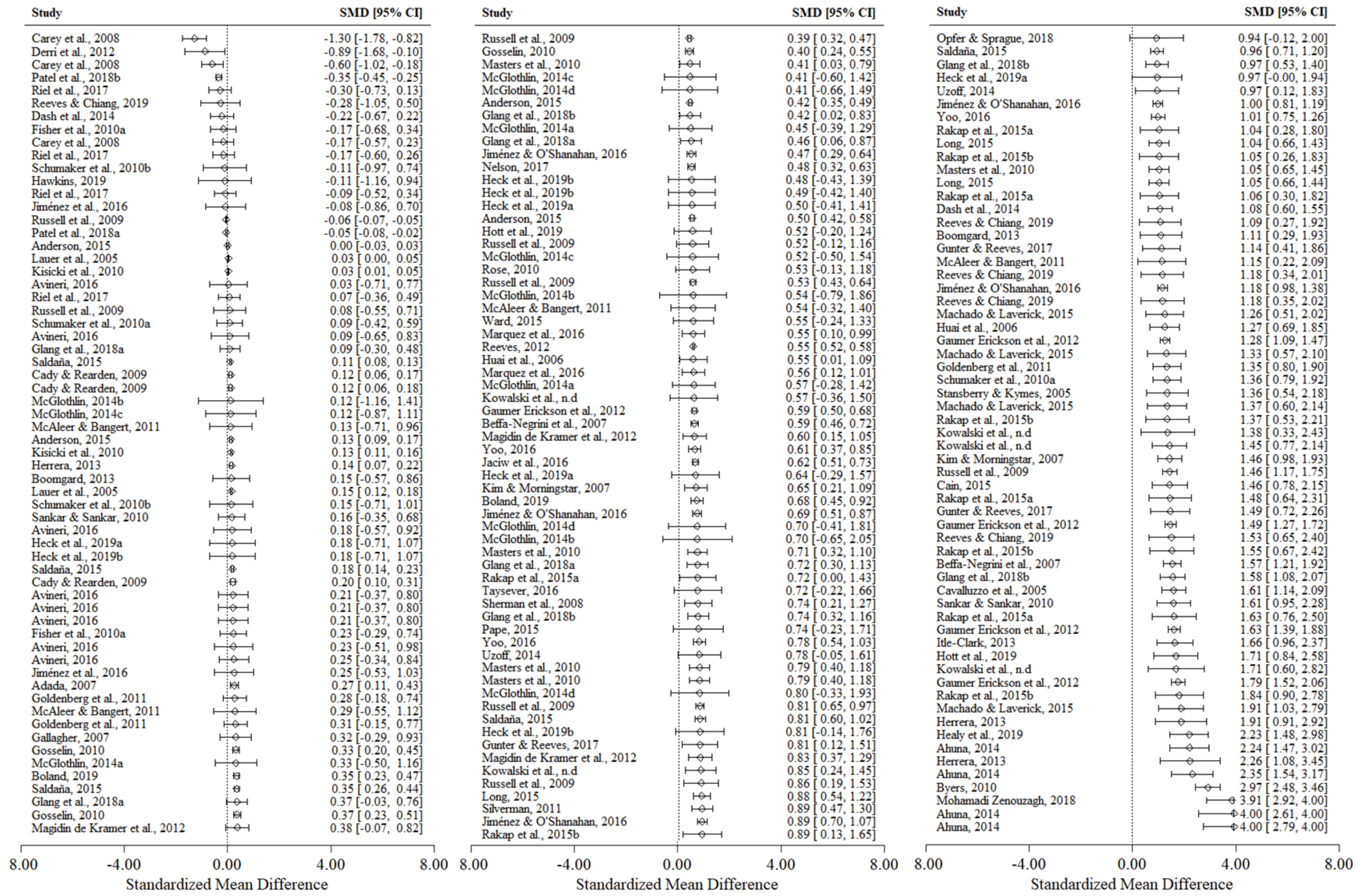


Table 3

Results of the Moderator Analysis on Study Characteristics. Note. OPD = online professional development, k = number of effect sizes.

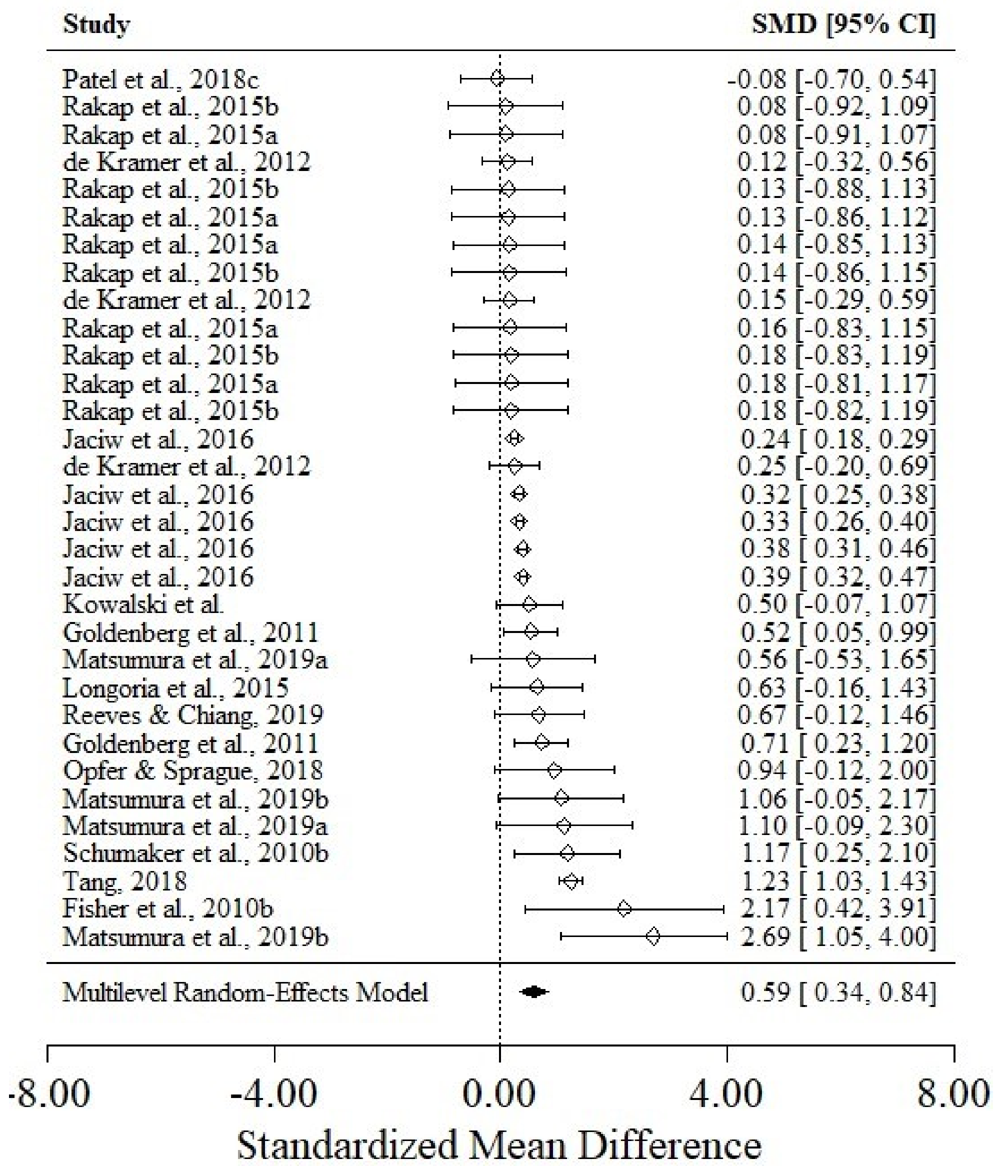
	Teacher level			Classroom level			Student level		
Moderator	*k*	b (*SE*)	*p*-value	*k*	b (*SE*)	*p*-value	*k*	b (*SE*)	*p*-value
Publication type									
Intercept (not peer-reviewed)	63	0.568 (0.127)	<.001	9	0.585 (0.218)	.007	15	0.225 (0.065)	<.001
Peer-reviewed	123	0.144 (0.162)	.373	23	0.020 (0.277)	.943	19	-0.046 (0.101)	.647
Study design									
Intercept (within-group)	140	0.757 (0.092)	<.001	13	0.274 (0.233)	.240	4	0.395 (0.124)	.001
CT	**46**	**-0.345 (0.170)**	**.042**	12	0.445 (0.309)	.150	30	-0.219 (0.132)	.098
Mode of PD									
Intercept (synchronous)	35	0.698 (0.184)	<.001	17	0.357 (0.205)	.081	8	0.378 (0.023)	<.001
asynchronous	130	-0.133 (0.203)	.514	10	0.285 (0.270)	.291	14	**-0.337 (0.026)**	**<.001**
Student population									
Intercept (non-special needs students)	127	0.693 (0.095)	<.001	10	0.774 (0.228)	<.001	20	0.127 (0.050)	.010
Special needs students	44	-0.038 (0.198)	.846	16	-0.498 (0.281)	.077	4	0.243 (0.095)	.011
Assessment									
Intercept (self-reports)	47	0.828 (0.152)	<.001	16	0.589 (0.224)	.009	4	0.187 (0.154)	.223
Standardized questionnaire	120	-0.266 (0.182)	.143	16	-0.011 (0.279)	.968	19	0.023 (0.167)	.889
both	13	0.141 (0.368)	.701	-	-	-	6	-0.063 (0.212)	.768
OPD Platform									
Intercept (online community)	13	0.464 (0.334)	.164	1	0.670 (0.448)	.135	7	0.304 (0.115)	.008
Website	28	0.321 (0.379)	.398	10	-0.230 (0.473)	.627	8	-0.177 (0.148)	.232
Online course	127	0.208 (0.348)	.550	18	-0.324 (0.463)	.484	13	-0.078 (0.141)	.580
Other	18	-0.026 (0.413)	.950	3	0.595 (0.489)	.224	6	-0.113 (0.160)	.480

Classroom Level

On the classroom level, OPD targets and measures outcomes including knowledge about classroom practice strategies, content knowledge of subjects, technological knowledge, teachers' attitudes and beliefs, teachers' self-efficacy, or other outcomes (a complete list and description can be found in Table S2, Supplementary Materials). The forest plot of the outcomes is depicted in Figure 8.

Figure 8

Forest Plot of Effect Sizes on the Classroom Level



Note. SMD = standardized mean difference (Hedges' *g*), CI = confidence interval.

For the moderator analysis (see Table 4), the moderator *collective participation* had a significant impact on the effect size, with studies reporting higher effect sizes that had a focus on collective participation in their program (k = 32, n = 12, β = 0.54, SE = 0.24, 95% CI [0.06, 1.02], p = .027).

Table 4

Results of Moderator Analysis of Core Feature of Effective Professional Development

Moderator	Teacher level *k*	b (*SE*)	*p*-value	Classroom level *k*	b (*SE*)	*p*-value	Student level *k*	b (*SE*)	*p*-value
Core feature: Content focus									
Intercept (no)	10	0.807 (0.307)	<.001	0			0		
Yes	174	-0.173 (0.318)	.586	31	0.580 (0.132)	<.001	34	0.205 (0.047)	<.001
Core feature: Active learning									
Intercept (no)	65	0.740 (0.133)	<.001	9	0.862 (0.215)	<.001	12	0.270 (0.076)	<.001
Yes	119	-0.147 (0.167)	.378	22	-0.438 (0.265)	.098	22	-0.106 (0.099)	.281
Core feature: Coherence									
Intercept (no)	41	0.664 (0.162)	<.001	0			0		
Yes	144	-0.002 (0.187)	.993	32	0.592 (0.128)	<.001	34	0.205 (0.047)	<.001
Core feature: Duration									
Intercept (no)		0.559 (0.107)	<.001		0.781 (0.205)	<.001		0.127 (0.092)	.165
Yes		0.000 (0.002)	.901		-0.005 (0.004)	.142		0.001 (0.001)	.628
Core feature: Collective participation									
Intercept (no)	124	0.739 (0.097)	<.001	19	0.355 (0.153)	.021	16	0.110 (0.067)	.101
Yes	60	-0.276 (0.167)	.098	12	**0.539 (0.244)**	**.027**	18	-0.165 (0.089)	.064

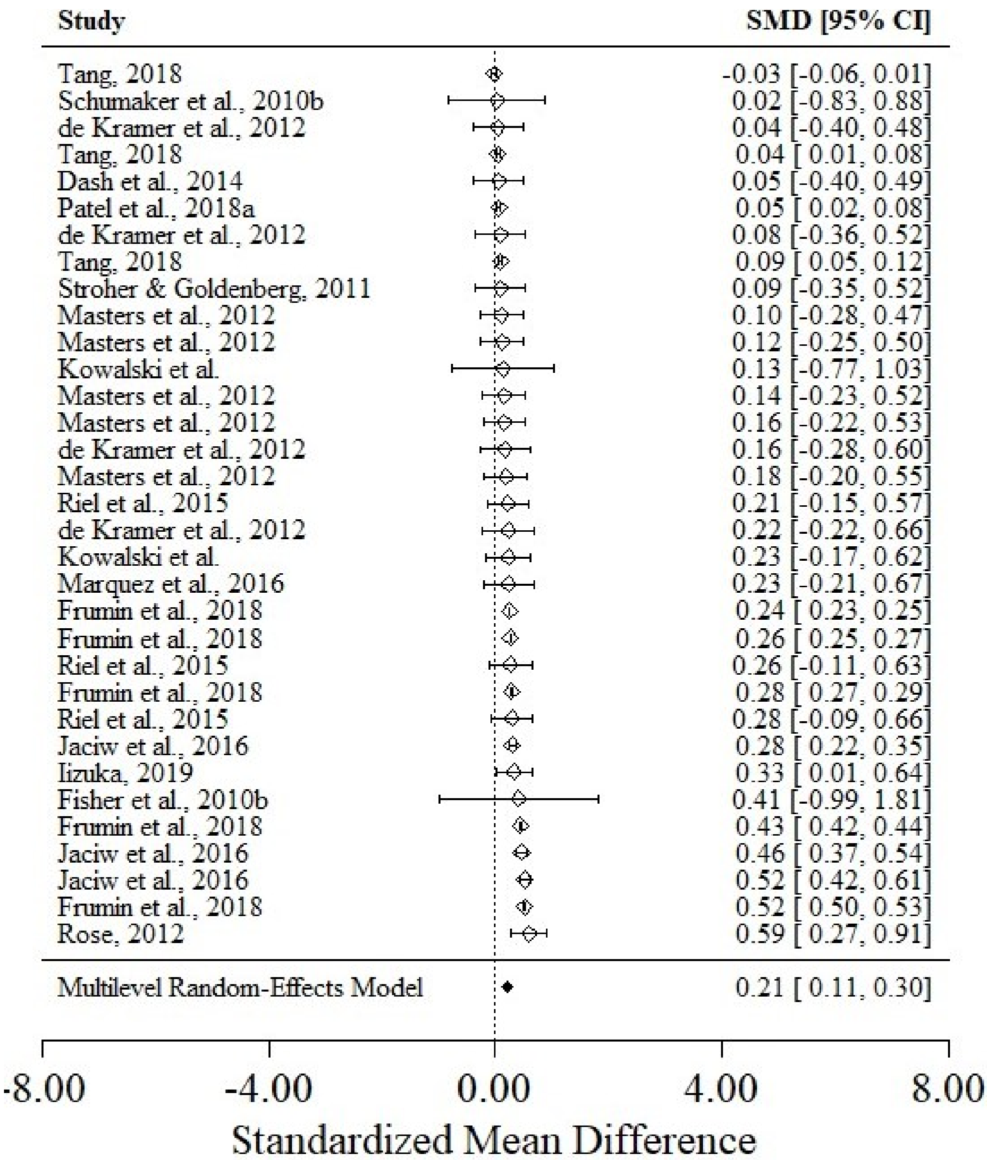
Note. PD = professional development, OPD = online professional development, *k* = number of effect sizes. The bold data are significant.

Student Level

On the student level, OPD targets outcome measures including content knowledge of subjects, achievement, classroom behavior, comprehension strategies, or others (a complete list and description can be found in Table S2, Supplementary Materials). For the forest plot, see Figure 9.

Figure 9

Forest Plot of Effect Sizes on the Student Level



Note. SMD = standardized mean difference (Hedges' *g*), CI = confidence interval.

For the moderator *mode of PD,* we found significantly smaller effect sizes for studies where the OPD was delivered synchronously compared to studies that delivered the OPD asynchronously (k = 33, n = 14, β = –0.34, SE = 0.03, 95% CI [–0.39, –0.29], p < .001; Table 5).

Table 5

Results of Moderator Analysis of Core Features of Effective Professional Development divided into Teachers' Knowledge and Teachers' Attitudes and Beliefs

	Teacher knowledge			Teacher attitudes and beliefs		
Moderator	*k*	b (*SE*)	*p*-value	*k*	b (*SE*)	*p*-value
Core feature: Content focus						
Intercept (no)	4	0.786 (0.453)	.083	6	0.760 (0.277)	.006
Yes	131	-0.039 (0.464)	.933	42	-0.255 (0.301)	.396
Core feature: Active learning						
Intercept (no)	46	0.876 (0.161)	<.001	19	0.672 (0.171)	<.001
Yes	89	-0.196 (0.200)	.327	21	-0.218 (0.224)	.332
Core feature: Coherence						
Intercept (no)	31	0.695 (0.181)	<.001	10	0.670 (0.222)	.003
Yes	105	0.086 (0.213)	.687	38	-0.139 (0.258)	.588
Core feature: Duration						
Intercept (no)		0.593 (0.128)	<.001		0.656 (0.154)	<.001
Yes		0.001 (0.003)	.649		-0.003 (0.003)	.429
OPD-activity: Collective participation						
Intercept (no)	104	0.759 (0.111)	<.001	19	0.749 (0.155)	<.001
Yes	31	-0.039 (0.225)	.863	29	-0.386 (0.212)	.068

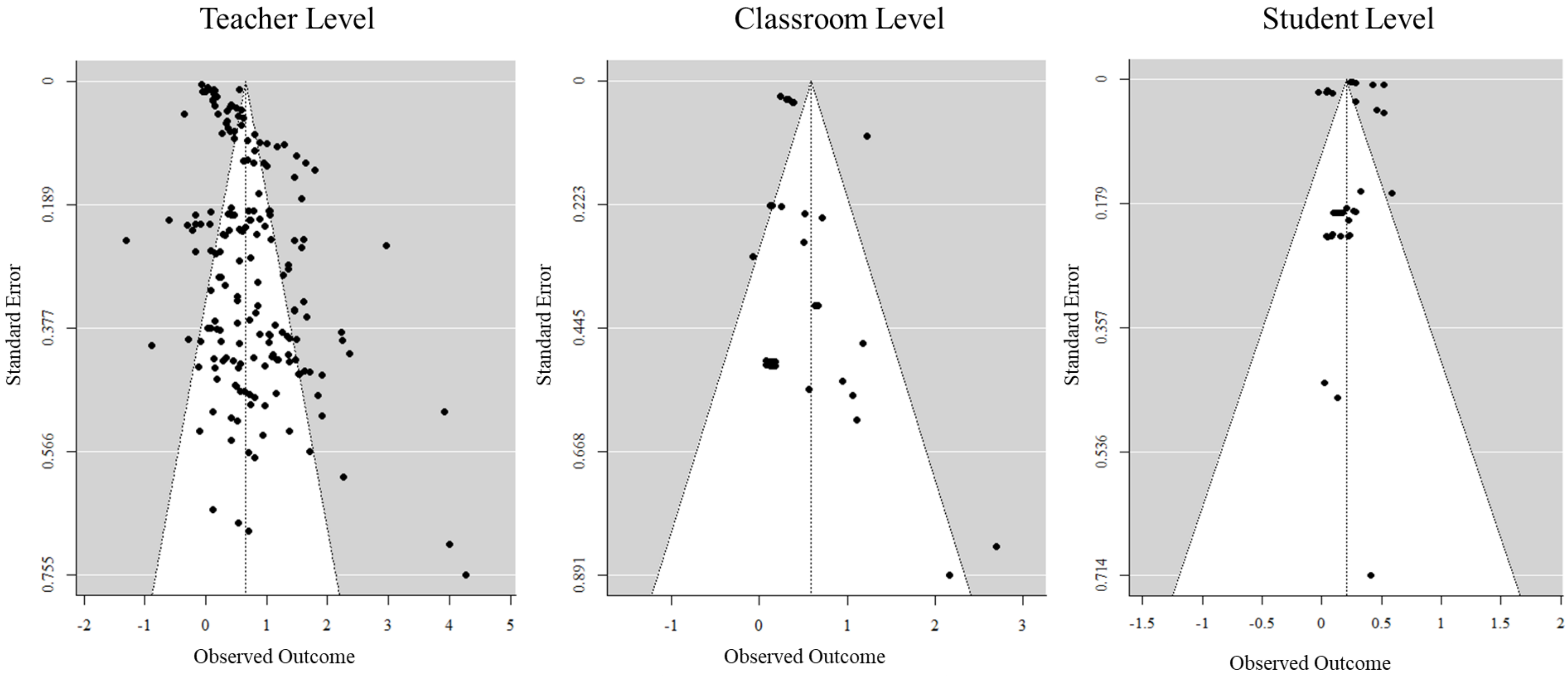
Note. OPD = online professional development, *k* = number of effect sizes. The bold data are significant.

Publication Bias

To investigate publication bias, we first used a moderator analysis with the publication type as a dichotomous moderator variable (1 = "peer-reviewed," 0 = "not peer-reviewed") to check whether published and peer-reviewed studies reported significantly smaller effect sizes, but that was not the case for the teacher and classroom level (see Table 3). However, on the student level (for the funnel plot, see Figure 10), the moderator analysis indicated that published studies reported a significantly smaller effect size than unpublished studies. Furthermore, we conducted a funnel plot analysis where the standard error of the studies is plotted against the effect size outcomes (Sterne & Egger, 2001). Without publication bias, the plot should resemble a symmetrical inverted funnel (Sterne et al., 2011). Furthermore, we conducted an Egger's formal test to examine publication bias (Egger et al., 1997). Egger's test is a regression analysis that tests asymmetry in the funnel plot. Asymmetry arises if the intercept of the regression model is significantly different from 0. In our sample, Egger's test has confirmed a slight publication bias for studies on the student level ($\beta = 0.24$, $z = 6.68$, $p <.001$). Neither the funnel plot (Figure 10) nor Egger's test indicated a significant publication bias for the teacher or classroom level.

Figure 10

Funnel Plot of Standardized Mean Differences in the Studies on Teacher Level, Classroom Level, and Student Level



Discussion

This meta-analysis set out to summarize the effectiveness of teacher participation in OPD on three levels of impact: on the teachers' knowledge, skills, attitudes, and beliefs; on their teaching practice within classrooms; and on their students' knowledge and achievement. Furthermore, this meta-analysis quantifies findings from 85 published and unpublished quantitative studies in 15 years. The results aim to give a comprehensive overview of the most up-to-date findings and implications of the effectiveness of teacher OPD. Although some systematic reviews (e.g., Bragg et al., 2021; Lantz-Andersson et al., 2018) have suggested that teacher participation in OPD has positive effects on teacher learning while others have found a negative impact of OPD (Kraft et al., 2018; Lynch et al., 2019), up to date, there is no meta-analysis quantifying the effects in such a comprehensive matter as this study. Unlike earlier studies, by incorporating gray literature, we aimed to tackle publication bias and summarize all findings within the field of teacher OPD.

The first main results of our study showed that OPD participation had a medium effect on the teacher level, increasing participating teachers' content knowledge, knowledge about classroom practices, and changes in attitudes, beliefs, and self-efficacy. These results mimic results found by other researchers in OPD participation. Studies investigating outcomes on the teacher level are the most common when assessing the effectiveness of OPD (e.g., Cavalluzzo et al., 2005; Gunter & Reeves, 2017; Jiménez et al., 2016), with most studies reporting high gains for participating teachers. Naturally, most OPD programs first target outcomes on the teacher level since they are the participating group and the ones who most need input regarding teaching practices. When considering Desimone's (2009) conceptual framework of effective PD and the additional literature in that field, the teacher level is the first level of the suggested change. Effective changes on the classroom and student level can only occur when changes in the teachers occur (Desimone, 2009).

Interestingly, we only found one significant moderator at the teacher level. We found that only the study design had a significant impact on the effect size, with studies that had a control-group design showing significantly lower effect sizes than studies that had a within-subjects design. No OPD features seemed to significantly impact the effect size on the teacher level. This is in line with Lynch et al. (2019) meta-analysis, which also did not find any significant impact of specific PD activities (i.e., observing demonstrations, reviewing students' work, solving problems, developing curriculum or lesson plans) on effect size magnitude on student achievement. Moreover, a meta-analysis by Kennedy (2016), albeit focusing on face-to-face-PD, questions the weight of program features, too, since they have not been shown to be significant predictors of program success.

Our second main result suggests that OPD participation of the teachers had a medium effect on their classroom practices. The most common OPD outcomes on this level were using instructional strategies and classroom management techniques. In accordance with models of effective teacher PD (Desimone, 2009; Darling-Hammond et al., 2009), change in classroom practice is the level that precedes students' change and, therefore, a fundamental level to target in PD. Changes in classroom practice are often subtle and difficult to measure as they need time to be implemented and, therefore, need to be investigated weeks or even months after the teachers' OPD participation. Most of the studies we incorporated into the meta-analysis used self-reported surveys or classroom observations right after the OPD was completed to quantify the changes on this level (e.g., Fisher et al., 2010; Rakap et al., 2015; Reeves & Chiang, 2019; Schumaker et al., 2010). On the classroom level, we found the moderator *collective participation* to be significant, with studies that incorporated this as a core feature of their OPD showing higher effect sizes than studies that did not. This is in line with other studies that have reported similar outcomes for teacher learning when the PD entailed collective participation activities (Armour & Makopoulou, 2012; Hauge, 2019).

The third main finding suggests that there was a small effect of teachers' OPD participation on the student level. Effects on the student level are not as immediate as on the teacher or classroom level. Typically, when effects on these levels occur, some time needs to pass for change to appear on the student level. As pointed out in an earlier systematic review by Yoon et al. (2007), changes in student achievement are tied to many factors of effective PD. Teachers must first understand and implement their new knowledge, skills, or attitudes in the classroom. Only then can effects on the student level be observed. The same pattern was also evident in Kennedy's (2016) meta-analysis of the effectiveness of face-to-face PD. She argues that effect sizes of .2 on the student level can be considered large, considering that two steps - changes in the teacher and classroom levels- have to precede the student level. This chain of effects can easily be diminished if there is a slippage in one of these steps. Interestingly, during the moderator analysis, we found that studies offering *asynchronous* OPD reported a smaller effect size on the student level than studies with *synchronous* OPD. One explanation might be that OPD, which targets the student level, might have a stronger content focus with more elaborated and complex content and might benefit more from a synchronous format. It might also indicate that teachers take the OPD more seriously when they attend it in a synchronous format.

Implications

The meta-analysis sheds light on the outcomes of participating in OPD and summarizes the current state of research regarding this topic. Even though we can conclude that OPD is effective on all outcome levels, as proposed by Desimone (2009), we can see a high heterogeneity between our study samples. Future research on this heterogeneity might be necessary to discern true effect sizes and potential confounders. Furthermore, we advise researchers to conduct more RCT in intervention studies so that group differences can be directly associated with the intervention.

Our study sets out to inspire policymakers to invest in building and providing highly effective OPD opportunities. With numerous advantages over traditional face-to-face formats, OPD can effectively elevate the PD experience through different formats like blogs and forums, enabling quality core features. However, we advise that OPD outcomes should not only focus on the immediate teacher level. Although the teacher level is arguably the most accessible level, there should also be an increased focus on acquiring more tangible skills or materials that teachers can implement in their classroom practice or when working with students. Furthermore, we aim to encourage educational stakeholders and teachers to participate in OPD while also considering features such as listening to audio files, sharing and acquiring ideas, the mode of delivery (synchronous/asynchronous), and the duration of the OPD.

Limitations

The limitations of our study depend mainly on the quality of the methodological design and the studies implemented into our analysis. First, most of the studies we included used a within-subject design. This design is not as reliable as randomized control-group designs since they can introduce biases (Greenwald, 1976).

Moreover, there are some restrictions to the data provided by some of the studies. For instance, some studies used questionnaires with several items to examine their outcome variables but then reported the mean of the items without providing a Cronbach’s alpha, which would be necessary to know whether the items can be summarized into one construct. We cannot guarantee that some information might be missing in these cases. Furthermore, when studies reported their outcome values in percentages instead of means, we converted them into numbers and used these values instead. If variables were reported as ranges (for example, the duration or teaching experience), we computed the mean and used this value for our variables. This process of converting reported values into the format we needed might have introduced some errors. For the moderator coding, we coded the activities the studies mentioned as a part of the OPD. However, there is no guarantee that teachers participated in the activity, which might skew the results of the moderator analysis. For example, a paper clearly stated that most participating teachers did not spend the intended time in OPD (Patel et al., 2018). Therefore, the coding of the moderator analysis is only an estimation of the best-case scenario of teacher participation. As one of the most important limitations, the moderator analysis only constitutes correlations between the moderator variable and the effect sizes of the studies. Therefore, it is not advisable to interpret the results as causal evidence.

Conclusion

In conclusion, the medium effect size on outcomes at the teacher level indicates that teachers benefit the most from their OPD participation. Effects on the classroom and student levels were significant but smaller than on the teacher level, suggesting that effects on these levels are not as apparent since teachers might need more time to integrate new knowledge and skills into the classroom so that their students can also benefit from their teachers' OPD participation. Certain features of OPD programs, like listening to audio files, duration, and mode of delivery, might moderate their effectiveness. Therefore, it might be necessary for OPD programs to include time and space for collaborative activities, whereas more research is needed to conclude which OPD features are most effective. Overall, our research suggests that the incorporation of additional OPD into teacher professional development programs has a favorable prospect.

Appendix

A

Google search terms

The Google Search terms were as follows:

Search term 1: “online professional development” teacher effect (achievement OR perform OR instruction OR practice OR belief OR skill OR attitude OR knowledge)

Search term 2: “online professional development” teacher effect (achievement OR perform OR instruction OR practice OR belief OR skill OR attitude OR knowledge)

Search term 3: “online professional development” teacher associated (achievement OR perform OR instruction OR practice OR belief OR skill OR attitude OR knowledge)

Search term 4: “online professional development” teacher impact (achievement OR perform OR instruction OR practice OR belief OR skill OR attitude OR knowledge)

Search term 5: “online professional development” teacher correlation (achievement OR perform OR instruction OR practice OR belief OR skill OR attitude OR knowledge)

B

Formulas to calculate r

$$r = \left(\left(s_1^2 t^2 + s_2^2 t^2\right) - \left(\bar{x}_2 - \bar{x}_1\right)n\right)/\left(2 s_1 s_2 t^2\right)$$

where r denotes the correlation coefficient, s_1 describes the standard deviation of the pretest score and s_2 the standard deviation of the posttest score, t denotes the t-value, denotes the mean of the pretest score and the mean of the posttest score, and *n* describes the sample size.

Supplementary

Table S1

Coding manual

VARIABLE	CODED AS	EXPLANATION
Study ID	Numerical	Each study gets an individual study ID, including multiple studies within one report
Author(s)	Character	Study Authors
Title	Character	Titel of the report
URL/doi	Character	URL/doi of the report
Year of publication	Numerical	Year of publication
Published? (peer-reviewed)	1- yes 0- no	Has the article been published and, very importantly, peer-reviewed?
If published, what from?	1- journal article 2- conference paper	Is the study part of a journal article or conference paper (proceedings)?
If not published, what form?	1- dissertation 2- report 3- manuscript/preprint	If the study was not published and peer-reviewed, in what form is the study available?
Journal / Publication outlet	Character	Name of the journal/publication outlet
Country Code	Character	Code of the country in which participant data were collected. Country codes can be found here: https://unstats.un.org/unsd/tradekb/Knowledgebase/50347/Country-Code
If subject, please specify	Character	Can the OPD activity be assigned to a specific school subject? Then, write down the subject(s)
OPD Objective: "Meta-Skill"?	Character	Can the OPD activity be assigned to general skills untied to specific school subjects?
More than one study?	0- no 1- yes	Was there more than one study described in the report?
Pre/post design	0- no 1- yes	Were data collected at least two times (before and after the intervention) in the study?
Follow-up	0- no 1- yes	Were data collected as a follow-up to the posttest after the intervention?
Study design	1- experimental 2- quasi-experimental 3- observational 4- descriptive 5- correlational 6- other	

Blended-PD?	0- no 1- yes	If parts of the OPD activity took place in person, this has to be coded as yes, and the study excluded from the sample
OPD Platform	1- online Community 2- (multi-media) Website 3- online course 4- list serves 5- other	1. Online community: The OPD takes mainly place within an online community via forums or social media sites. What defines an online community is that members interact with each other, that content is often personalized, and that individual questions and difficulties are addressed through communication with other members 2. Website: Here, different media types are made available. A website is provided to bundle different media in one place. Access is provided through a link, which is sometimes also mentioned in the article. Participation is often asynchronous. 3. Online course: Has the character of a workshop, which theoretically could also take place face-to-face. The course is often "modular" or has a "temporal dimension", e.g., certain contents are only available within a certain time. Often, a module needs to be completed to access more modules; the knowledge is built up successively. 4. list serves: E-mail lists, exchange between a participant and teacher educator/mentor 5. Other: every other platform that does not fit into the previous descriptions
OPD feature- content focus	0- no 1- yes	- sharing/acquiring resources: Teachers exchange (teaching) resources among themselves or acquire resources from websites or teacher educators. Within the OPD, resources are made available to the participants, for example, as downloads. Resources are more tangible than ideas and insights, and include books, articles, slides, or other materials. - sharing ideas and insights: Teachers share ideas, insights, and experiences. Ideas can also be provided by websites, researchers, or teacher educators. Ideas and insights are usually more personal. The activity of sharing ideas and insights must be explicitly mentioned in the text. - video watching: Videos or animations with a content focus were watched during the OPD, the length of the videos does not matter - text reading: Texts with a content focus that inform the teachers are being read (including professional literature/handbooks/guidelines) - audio listening: Teachers listen to audio files or podcasts as an activity of the OPD.
OPD feature- active learning	0- no 1- yes	- participating in and leading discussions: There is discussion, perhaps in the form of forum posts. Discussions can be defined as the act or process of talking or debating about some topic to decide. - asking questions: Questions are actively asked, and answers are expected in return. Questions can also take place in the context of a discussion. However, the focus of this activity is on getting quick answers and filling information and knowledge gaps. - reflective writing: Teachers write short texts, often reflecting on their own behavior or the observation of others' teaching practices. Texts can be in the form of journals, diary entries, blogs, or feedback rounds.

OPD feature- collective participation	0- no 1- yes	- collaboration with educators: Close collaboration with a "teacher educator", i.e., someone who provides information, materials, etc., and is a contact person/mentor. Often such teacher educators are formally trained for their position - networking: Networking is about building contacts and exchanging ideas intensively and actively with one another, even in the long term. Networking is often a byproduct of "online communities". New relationships develop between teachers who would not have met in real life. - emotional support: Teachers can express their emotions like frustration, joy, fears, and other emotions and receive emotional support in return.
OPD feature- coherence	0- no 1- yes	- external coherence: PD coherent with external factors, b) - internal coherence: Program and content of the PD is aligned - in-create coherence: PD's focus is to create more coherence for teachers within their teaching, school context, and curriculum demands.
OPD activities - if other please specify	Character	If other activities were part of the OPD, please write them down here.
Fieldwork/survey year start	Numerical	Start of data collection
Fieldwork/survey year end	Numerical	End of data collection
Dataset Teacher ALL sample size	Numerical	Sample size of all in-service teachers
Dataset control group design	1- randomized intervention/control group design 2- non-randomized intervention/control group design 3- only intervention, randomized 4- only intervention, non-randomized	
What happened to the control group?	1- business as usual 2- face-to-face course 3- other OPD	Did the control group also participate in an intervention, if so what kind of intervention? Business-as-usual means no particular intervention
Dataset Teacher all gender distribution	Numerical	All female participant in the dataset (in %)
Dataset teacher intervention group sample size	Numerical	Number of teachers who were assigned to the intervention (only complete data)
Dataset teacher intervention group gender distribution	Numerical	Female participants in the intervention group (in %)
Dataset teacher control group sample size	Numerical	Number of teachers assigned to the control group (complete data sets only).

Dataset teacher control group gender distribution	Numerical	Female participants in the control group (in %)
Dataset sample size all students	Numerical	Sample size of students whose teachers participated in the study (both control and intervention group)
Dataset sample size treatment group students	Numerical	Sample size of students whose teachers participated in the study in the intervention group
Dataset sample size control group students	Numerical	Sample size of students whose teachers were assigned to the control group
Student grades	1- kindergarten 2- pre-school 3- elementary school 4- middle school 5- high school	In which grades were the students at the time of data acquisition?
Student population- special needs students?	0- no 1- yes	Are the students a "special needs" group, meaning with impairments or in need of special assistance? May include physical impairment or mental impairment
Student population- special needs students? please specify	Character	If yes, please specify
Teaching experience	Numerical	mean (in years)
Online OPD duration	Numerical	in hours (on average, how long was the activity available to teachers?)
Online OPD duration Category (in hours)	1- 1 to 19 2- 20 to 39 3- 40 to 59 4- 60 to 79 5- 80 to 99 7- 100+	on average, how long was the activity available to teachers?
OPD self-paced?	0- no 1- yes	Was the OPD completely asynchronous?
OPD mandatory?	0- no 1- yes	Was the OPD mandatory for the teachers?
Questionnaire type	1- self-report 2- standardized test 3- both	Type of questionnaire with which data were acquired
if standardized test, please specify	Character	Please note the name of the standardized test, if reported in study
Examined teacher outcomes	0- no 1- yes	Were outcomes on the teacher level investigated?
Examined classroom outcomes	0- no 1- yes	Were outcomes on the classroom level investigated?
Examined student outcomes	0- no	Were outcomes on the student level investigated?

	1- yes	
*Teacher variable 1	Character	What was the outcome that was measured?
* TV 1 Test for outcome measurement, please specify (e.g., ANOVA, t-test, correlation)	Numerical	Please specify the statistical method used to calculate the significance/size of the outcome
*Page number where effect size data can be found	Numerical	Page number of outcome measurement
*Difference favors (shows more success for)	1- intervention group 2- neither/not significant 3- control group 4- both groups 5- cannot tell	Is there a statistically significant effect that occurred after the intervention? In which group did this occur? 1- only the intervention group shows a significant increase in their T/C/S outcome after participating in the OPD. 2- neither the intervention group nor the control group has significant improvements 3- only the control group has a significant improvement 4- both groups have a significant improvement 5- it is not clear from the text
*Intervention group mean (pretest)	Numerical	The pretest mean of the outcome of the intervention group
*Intervention group SD (pretest)	Numerical	The pretest SD of the outcome of the intervention group
*Control group mean (pretest)	Numerical	The pretest mean of the outcome of the control group
*Control group SD (pretest)	Numerical	The pretest SD of the outcome of the control group
*Intervention group mean (posttest)	Numerical	The posttest mean of the outcome of the intervention group
*Intervention group SD (posttest)	Numerical	The posttest SD of the outcome of the intervention group
*Control group mean (posttest)	Numerical	The posttest mean of the outcome of the control group
*Control group SD (posttest)	Numerical	The posttest SD of the outcome of the control group
*Significance test (e.g., t-value, F-value, chi-square), please specify	Numerical	

Note. OPD = online professional development, PD = professional development, SD = standard deviation, TV = teacher variable, * = rows marked with an asterisk are duplicated for classroom level and student level outcomes. Up to 5 different outcomes can be coded, for each outcome, the rows with asterisks are also duplicated.

Table S2

Complete list of studies included in the meta-analysis

Study	Design	Con-trol group	Level	OPD outcome	Country	N Inter-vention	N control	Peer-re-viewed	hours OPD	Platform
Adada, 2007	WSD	-	T	Change in attitude toward the usage of technology in the classroom	USA	312	-	NPR	1 to 19	Other
Ahuna, 2014	WSD	-	T	Comfort using online mini training to learn and understand of Committee Minutes application	USA	16	-	PR	-	WS
Anderson, 2015	WSD	OPD	T	Correlation minutes of participation and teacher self-efficacy of student engagement, teacher self-efficacy of student engagement, instructional strategies, and classroom management	USA	45	41	NPR	100+	OCOM
Anderson et al., 2011	RWSD	OPD	T, C	Teachers' use of digital media, interactive activities, teachers' knowledge and comfort level of digital media use in the classroom, teachers' belief about digital media	USA	37	-	PR	20 to 39	OC
Avineri, 2016a	WSD	-	T	Mathematical knowledge, fraction introduction, effective use of fair sharing activities, knowledge of mathematical measurement and mathematical operations	USA	54	-	NPR	-	OC
Avineri, 2016b	WSD	-	T	Mathematical knowledge, fraction introduction, effective use of fair sharing activities, knowledge of mathematical measurement and mathematical operations	USA	140	-	NPR	-	OC
Beffa-Negrini et al., 2007	WSD	-	T	Comfort and knowledge in teaching food safety	USA	38	-	PR	20 to 39	OC
Boland, 2019	WSD	-	T	Self-efficacy of technology use in a Chinese context, technology integration knowledge, and abilities	CN	16	-	NPR	20 to 39	OC

Boomgard, 2013	WSD	-	T	Teacher self-efficacy about working with students with autism, teachers' perception of burnout	USA	15	-	NPR	-	OC
Byers, 2010	WSD	-	T		USA	102	-	NPR	-	OC
Cady & Rearden, 2009	WSD	-	T	Pedagogical content knowledge on numbers and computation, algebra, geometry, and measurement	USA	8		PR	-	OC
Cain, 2015	WSD	-	T	Teacher self-efficacy of their classroom instructions	USA	25	25	NPR	-	WS
Carey et al., 2008	RWSD	OPD	T	Teacher-directed pedagogical beliefs, student-centered pedagogical beliefs, general technology use in the classroom	USA	48	49	PR	-	OC
Cavalluzzo et al., 2005	WSD	-	T	Understanding of the material, assessment reading, and literacy instructions	USA	693	-	PR	-	OC
Dash et al., 2012	RCT	BAU	T, S	Teachers' pedagogical content knowledge and practices, students' mathematical achievement	UK	34	45	PR	60 to 79	OC
Derri et al., 2012	RCT	FTF	T	Knowledge of general assessment and inclusive assessment practices	GRC	14	13	PR	1 to 19	WS
Fisher et al., 2010a	RCT	FTF	T	Teacher knowledge of the concept teaching routine	USA	30	29	PR	1 to 19	other
Fisher et al., 2010b	RCT	FTF	C, S	Teachers' performance of targeted instructional behaviors during a classroom lesson about a concept	USA	4	4	PR	1 to 19	other
Frumin et al., 2018	CT	BAU	S	AP Science Score Biology, AP Science Score Chemistry, AP Science Score Physics	USA	1298	964	PR	-	OCOM
Gallagher, 2007	WSD	-	T	Computer self-efficacy	USA	21	-	NPR	-	OC
Gaumer Erickson et al., 2012	WSD	-	T	Competency in transition-related skills, knowledge of curriculum-referenced assessments	USA	86	63	PR	100+	OC
Glang et al., 2018a	RWSD	OPD	T	Teachers' knowledge of working with students with TBI, teachers' competency in applying TBI knowledge to fictive scenarios, teachers' applied self-	USA	50	-	PR	1 to 19	OC

				efficacy, teachers' confidence in effectively implementing various instructional strategies for students with TBI						
Glang et al., 2018b	RWSD	OPD	T	Teachers' knowledge of working with students with TBI, teachers' competency in applying TBI knowledge to fictive scenarios, teachers applied self-efficacy, teachers' confidence in effectively implementing various instructional strategies for students with TBI	USA	50	-	PR	1 to 19	WS
Gosselin, 2010	WSD	-	T	Science teaching outcome expectancy of NASA-Sponsored Laboratory Earth, personal science teaching efficacy beliefs, beliefs about science	USA	13	-	PR	-	OC
Gunter & Reeves, 2017	WSD	-	T	Attitudes toward mobile learning, perceived learning of mobile device use in the classroom, perceived engagement of mobile device use in the classroom	USA	91	-	PR	-	OC
Hawkins, 2019	RCT	BAU	T	Teacher knowledge of concussion symptoms and classroom support of concussed students	USA	7	7	NPR	1 to 19	OC
Healy et al., 2019	RCT	BAU	T	Content knowledge of peer tutoring	USA	21	23	PR	1 to 19	OC
Heck et al., 2019a	WSD	OPD	T	Preparedness to teach algebra, algebra content knowledge, use of context in teaching algebra, analyzing student work, and making instructional suggestions	USA	26	-	PR	20 to 39	other
Heck et al., 2019b	WSD	OPD	T	Preparedness to teach algebra, a string of problems as a pedagogical strategy for developing targeted algebra ideas, use of context in teaching algebra, analyzing student work, and making instructional suggestions	USA	26	-	PR	20 to 39	other
Herrera, 2013	RWSD	-	T	Beliefs about the importance and value of art instructions, arts-integrated teaching, teacher confidence and self-efficacy with the arts, teacher's knowledge about visual art and drama vocabulary and processes	USA	7	-	NPR	-	OC

Hott et al., 2019	WSD	-	T	Knowledge of algebra strategies, the relationship between teacher knowledge and the use of algebra strategies	USA	66	-	NPR	1 to 19	other
Huai et al., 2006	CT	OPD	T	Knowledge and self-efficacy of general assessment and inclusive assessment practices	USA	29	26	PR	-	WS
Iizuka, 2019	RWSD	-	S	Students perceived strength and difficulties, students perceived anxiety	USA	41	-	NPR	1 to 19	OCOM
Itle-Clark, 2013	RWSD	-	T	Knowledge of strategies for integrating humane education concepts into the classroom	USA	26	-	NPR	-	OC
Jaciw et al., 2016	RCT	BAU	T, C, S	Teacher self-confidence in literacy instruction, teachers instructing/modeling metacognitive inquiry strategies, teacher employing traditional teaching methods, students practicing in metacognitive inquiry strategies, students practicing comprehension strategies	USA	35	34	NPR	60 to 79	OC
Jiménez & O'Shanahan, 2016	WSD	-	T	Knowledge of phonological awareness in Spanish learners, alphabetical knowledge, skills of Spanish learners, knowledge of the value of oral and written Spanish vocabulary, knowledge of Spanish fluency and its components, knowledge of Spanish oral and written comprehension	ESP	270	-	PR	-	OC
Jiménez et al., 2016	RCT	BAU	T	Teacher knowledge of data collection and data-based decisions, teacher ability to make a data-based decision and suggest an instructional plan with simulated data scenarios	USA	15	11	PR	1 to 19	OC
Kim & Morningstar, 2007	RCT	BAU	T	Teachers' knowledge gains and competency gains on working with CLD families	USA	43	42	PR	1 to 19	OC
Kisicki et al., 2010	RCT	-	T	Teacher knowledge of Arizona geography and water systems	USA	74	68	NPR	-	OC

Kowalski et al., n.d.	RWSD	-	T, C, S	Teachers' content knowledge about energy concepts, ability to analyze videos, use of key teaching practice strategies, students' content knowledge about energy concepts	USA	25	-	NPR	100+	OC
Lauer et al., 2005	CT	BAU	T	Teacher profession efficacy, integration of technology into classrooms	USA	43	97	PR	-	OCOM
Long, 2015	RWSD	OPD	T	Self-efficacy of teaching practices in STEM, teaching outcome expectancy of science teaching in general, content knowledge of Force of Motion (physical concept)	USA	10	7	NPR	1 to 19	OC
Longoria et al., 2015	WSD	-	C	The positive impact of PD on teaching practice	USA	48	999	PR	-	WS
Machado & Laverick, 2015	WSD	-	T	Teachers' general technology knowledge, teachers' general pedagogy knowledge, teachers' content knowledge of their respective fields, teacher's general TPACK knowledge	USA	19	-	PR	40 to 59	OC
Magidin de Kramer et al., 2012	RCT	BAU	T, C, S	Teachers' knowledge of learning and teaching vocabulary, English literacy and reading comprehension, teachers' overall knowledge of English language arts, teachers' use of instructional practices, using technology to teach writing, students' depth of English word knowledge and context, students' English reading comprehension knowledge, and strategies, students' English writing practices comprehension	USA	35	45	PR	100+	WS
Marquez et al., 2016	RCT	BAU	T, S	Teacher self-efficacy of using classroom management in action program, knowledge of classroom management, students' classroom behavior	USA	34	49	PR	11 to 19	OC
Masters et al., 2010	RCT	BAU	T	Teachers' knowledge of English language arts vocabulary and identification of words, knowledge related to research-based reading comprehension strategies, knowledge related to the traits of good	USA	49	61	PR	100+	OC

				writing and the writing process, best practices in vocabulary instructions						
Masters et al., 2012	RCT	BAU	S	Students' vocabulary knowledge, students reading comprehension knowledge, students writing knowledge, students' overall English language knowledge, knowledge related to research-based reading comprehension strategies	USA	766	922	PR	100+	OC
Matsumura et al., 2019	WSD	-	C	Teachers' classroom text discussion quality	USA	7	-	PR	-	other
Matsumura et al., 2019	WSD	-	C	Teachers' classroom text discussion quality	USA	8	-	PR	11 to 19	other
McAleer & Bangert, 2011	WSD	-	T	Perception of enhancement of the use of technology, mathematical content knowledge, reflective practices, and curriculum content	USA	34	-	PR	1 to 19	OC
McGlothlin, 2014a	WSD	-	T	Content knowledge, pedagogy knowledge	USA	36	-	NPR	-	OC
McGlothlin, 2014b	WSD	-	T	Content knowledge math, pedagogy knowledge math	USA	6	-	NPR	-	OC
McGlothlin, 2014b	WSD	-	T	Technology knowledge social studies, content knowledge social studies	USA	13	-	NPR	-	OC
McGlothlin, 2014c	WSD	-	T	Content knowledge sciences, pedagogy knowledge science	USA	17	-	NPR	-	OC
Mohamadi Zenouzagh, 2018	WSD	-	T	Teaching competency improvement in English as a foreign language	KOR	30	-	PR	-	WS
Nelson, 2017	WSD	-	T	Data-informed decision-making practices in the classroom	USA	19	-	NPR	-	OC
Opfer & Sprague, 2018	RWSD	-	T, C	Teachers' belief that OPD is beneficial to their professional growth, teachers' feeling comfortable	USA	18	-	NPR	-	WS

				transferring the learned content knowledge into their instructional practices						
Pape, 2015	WSD	-	T	Mathematical content knowledge	USA	23	-	PR	-	OC
Patel et al., 2018a	RCT	BAU	T	Teachers' knowledge and understanding of standards-based, EL-relevant instructional practices	USA	48	43	NPR	20 to 39	WS
Patel et al., 2018b	CT	BAU	C	Teachers' knowledge and understanding of standards-based, EL-relevant instructional practices	USA	18	25	NPR	20 to 39	WS
Patel et al., 2018c	CT	BAU	C	Use of all ED-Conx-supported instructional practices	USA	257	271	NPR	20 to 39	WS
Rakap et al., 2015a	RWSD	OPD	T, C	Teacher competency and knowledge of working with students with autism spectrum disorders, teacher comfort level in using visual teaching strategies, classroom management strategies, communication skills, social skills, teaching strategies for challenging behaviors	USA	17	-	PR	1 to 19	OC
Rakap et al., 2015b	RWSD	OPD	T, C	Teacher competency and knowledge of working with students with autism spectrum disorders, teacher comfort level in using visual teaching strategies, classroom management strategies, communication skills, social skills, teaching strategies for challenging behaviors	USA	16	-	PR	1 to 19	OC
Reeves & Chiang, 2019	RCT	BAU	T, C	Data use in the classroom, anxiety, self-efficacy of data identification and access, self-efficacy of data technology use, knowledge of data analysis and interpretation, knowledge of the application of data to instruction, in-school implementation of data use practices	USA	12	14	PR	1 to 19	OCOM
Reeves, 2012	WSD	-	T	Beliefs in the effectiveness of OPD	USA	11397	-	PR	20 to 39	OC
Riel et al., 2015	CT	-	S	Students' science confidence, learning skills confidence, and science career interest	USA	4	4	NPR	-	WS

Riel et al., 2017	WSD	-	T	Confidence to teach science in a social studies classroom, teachers’ confidence in teaching writing skills, confidence in implementing the curriculum productively, confidence in facilitating student-centered inquiry pedagogies with students	USA	42	-	PR	-	WS
Rose, 2010	WSD	-	T	Teacher knowledge about environmental processes and environmental consequences of humans	USA	19	-	PR	1 to 19	other
Rose, 2012	WSD	-	S	Students’ knowledge about environmental processes and environmental consequences of humans	USA	96	-	NPR	-	other
Russell et al., 2009a	RWSD	FTF	T	Teachers’ understanding of the base ten number system and related concepts, teacher confidence in teaching mathematics, teacher-directed beliefs, Student-centered beliefs, comfort in recognizing students’ problem-solving strategies	USA	49	-	PR	20 to 39	OC
Russell et al., 2009b	WSD	-	T	Confidence in teaching mathematics, confidence in mathematical skills, teachers’ confidence in technology use	USA, CAN	106	-	PR	20 to 39	OC
Saldaña, 2015	RWSD	OPD	T	Teacher technological knowledge for technology integration in the classroom, math content knowledge, social studies content knowledge, science content knowledge, and literacy content knowledge	USA	29	-	NPR	-	OC
Sankar & Sankar, 2010	RWSD	FTF	T	Knowledge to co-teach in a classroom with students with special needs	USA	29	31	PR	-	WS
Schumaker et al., 2010a	RCT	FTF	T	Knowledge about concept comparison routine, teachers’ knowledge and skills related to completing a concept comparison table	USA	28	32	PR	1 to 19	other
Schumaker et al., 2010b	RCT	FTF	T, S, C	Knowledge and understanding of content comparison components and procedures, teachers’ knowledge and skills related to completing a concept comparison table, implementation of classroom practices for	USA	11	10	PR	1 to 19	other

				concept comparison, students' understanding of two concepts taught in the lesson						
Sherman et al., 2008	RWSD	-	T	Teachers' scores at Newtonian force and motion word problem application	USA	31	-	PR	1 to 19	WS
Silverman, 2011	WSD	-	T	Teachers' mathematical knowledge, ability to solve mathematical problems	USA	54	-	PR		OC
Stansberry & Kymes, 2005	RWSD	-	T	Teachers' likeliness to use instructional technology tools for class preparation or in class	USA	66	-	PR	-	OC
Strother & Goldenberg, 2011	CT	BAU	S	Content knowledge on genetics and evolution	USA	1110	2238	PR	-	OC
Tang, 2018	WSD	OPD	C, S	Time allocated in quality cooperative/collaborative/peer-tutoring strategies, students' oral reading fluency, comprehension knowledge, and oral expression	USA	38	39	NPR	-	other
Taysever, 2016	WSD	-	T	Behavior and perception regarding science, technology, engineering, arts, mathematics teaching	USA	26	-	NPR	-	OC
Uzoff, 2014	WSD	-	T	Personal science-teaching efficacy and correlation with experience of communities of practice, science outcome teaching expectancy and correlation with experience of communities of practice	USA	44	-	NPR	-	OCOM
Ward, 2015	WSD	-	T	Self-efficacy with the implementation of 2.0 Web Tools in classroom practice	USA	48	-	NPR	-	WS
Yoo, 2016	WSD	-	T	Self-efficacy in instructional strategies, self-efficacy in classroom management, self-efficacy in student engagement	USA	148	-	PR	-	OC

Note. RCT = randomized controlled trial, CT = non-randomized controlled trial, WSD = within-subject design, RWSD = randomized within-subject design, BAU = business as usual, FTF = face-to-face PD, OPD = other OPD, T = teacher level, C = classroom level, S = student level, PR= peer-reviewed, NPR = not peer-reviewed, OC = online course, WS = website, OCOM = online community

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Study 2

Morina, F., Hübner, N., Eisenkraft, A., & Fischer, C. (2024). *Examining Laboratory Investigations in Advanced Placement Biology: Teachers' Perceived Challenges and Their Classroom Practice.* The manuscript was submitted for publication in the *Journal of Science Education* and is currently under review.

This version of the manuscript might not exactly replicate the final published journal article. It is not the copy of record.

Abstract

Inquiry learning can promote the development of meta-cognitive skills in students. Therefore, science education reforms have emphasized inquiry learning within laboratory investigations, and teachers are responsible for enacting reform efforts in their classroom practice. This study investigates the number of laboratory investigations and inquiry learning in teachers' classroom practice in response to educational reform and their perception of challenges. Data includes 1,721 biology teachers' responses in the first three years after redesigning the Advanced Placement (AP) Biology curriculum in the United States. Applying latent growth curve modeling, we examined teachers' perceived challenges concerning laboratory investigations and the number of laboratory investigations implemented in their instruction. We found that perceived challenges decreased over time while the number of laboratory investigations increased. Participation in online professional development activities helped teachers implement more laboratory investigations in the first reform year. Following educational reforms, educational stakeholders should provide more PD opportunities to address the challenges teachers perceive related to the reform.

Keywords: laboratory investigations, educational reform, teacher professional development, biology education, Advanced Placement

Introduction

High school graduates' science, technology, engineering, and mathematics (STEM) knowledge and skills have become increasingly important to national economies, as demonstrated by many international reports and recommendations (National Research Council, 2013a; National Science Board, 2007). High school students should pursue STEM careers and develop problem-solving and reasoning skills. International educational reforms have facilitated these outcomes, such as revisions to Japan's National Curriculum Standards (Yamanaka & Suzuku, 2020), Qatar's constructivist teaching methods (Zimmerman et al., 2017), Turkey's biology education reform (Irez & Han, 2011), and changes to Finland's National Framework Curriculum (Lavonen, 2020). These revised curricula and exams shift their former emphasis on rote learning and memorizing facts to classroom practices that help students acquire conceptual knowledge, problem-solving skills, and reasoning skills (e.g., National Research Council, 1996; Committee on Prospering in the Global Economy of the 21st Century, 2007). In the US, K-12 education is guided by the National Research Council (NRC) and the Next Generation Science Standards (NGSS), which define eight practices. These include asking questions, developing and using models, planning and carrying out investigations, analyzing data, using mathematics and computational thinking, constructing explanations and designing solutions, engaging in arguments from evidence, and obtaining, evaluating, and communicating information. Therefore, natural science classes curriculum reforms have emphasized laboratory investigations as science practices that allow students to participate in these eight practices (National Research Council, 2012). As a natural science, biology education is concerned with understanding organisms, their functions, and their interactions. In class, these processes can often be observed directly through laboratory investigations (often called *labs*) with little effort and few tools, giving students opportunities for hands-on experience (College Board, 2012). Labs can range from structured experiments that follow clear guidelines to open inquiry learning, where students investigate their scientific ideas through self-selected methods and experiments, with or without the teachers' guidance (Bell et al., 2005). Through engaging in labs and inquiry learning, students acquire factual knowledge and an authentic understanding of the nature of science (National Research Council, 1996, 2000; Geier et al., 2008; Hanauer & Dolan, 2014).

With the importance of labs and inquiry learning acknowledged by many high-profile institutions, the College Board redesigned its Advanced Placement (AP) Biology program in the United States to incorporate more labs and inquiry opportunities into classroom practice (College Board, 2012). Incorporating labs is a new challenge for teachers, who are the most critical change agents in reform efforts and need ongoing support to navigate significant changes to their usual classroom practice. Therefore, AP Biology teachers were given professional development (PD) opportunities by the College Board to help with the challenges of implementation. The provided PD activities consisted of materials and resources for teachers, opportunities for collegial support, spaces for Q&A (e.g., through face-to-face and online workshops), and access to an online AP teacher community (APTC; Frumin et al., 2018). This study investigates the interplay between educational reform in science, laboratory investigations, inquiry learning, and PD for teachers. It informs educational stakeholders, policymakers, and teachers about ways of successful reform implementation.

Teacher Concerns During Educational Reforms

Teachers play an essential role in reform implementation, resulting in many concerns and fears (Datnow, 2020). Concerns are feelings, thoughts, preoccupations, and considerations given to an issue or task, directly affecting performance and implementation (Hall & Hord, 2015). Hall et al. (1973) identified teacher concerns and their implication for enactment of innovation in the Concerns-Based Adaption Model (CBAM), which states that teachers' concerns carry through different stages of innovation implementation. Teachers first have little knowledge of the innovation and then express concerns about it. Later, they focus on methods to manage the innovation, how it affects their students, relate their actions to their colleagues, and evaluate the innovation (Christou 2004). Research has also shown that most teachers perceive concerns change over time with experience of the reform (Charalambous & Philippou, 2010; Christou et al., 2004; Fischer et al., 2018a; Geng et al., 2019).

Laboratory Investigations in Biology Education

Inquiry learning involves a student-centered, active learning approach by having students autonomously conduct experiments and make observations (Pedaste et al., 2012). Notably, inquiry learning is not a closed system and can be best described on a spectrum encompassing active learning opportunities at different levels (e.g., Banchi & Bell, 2008; Furtak et al., 2012). At the structured level, students investigate a research question presented by their teacher using fixed experimental procedures. This is the definition of typical labs. At a guided inquiry level of labs, students investigate a research question presented by their teacher. However, students designed the experimental procedure for their research questions themselves. At an open level, the students design both the research question and the experimental procedure (College Board, 2022a). For example, students learn about the theory of a biological concept, like cell respiration, and are then asked to design an experiment to investigate their questions.

In the biology classroom, inquiry learning is mainly carried out within labs, which often have a definite purpose, focus on the process of science to learn new concepts, incorporate student reflection and discussion, and enable students to develop lab habits and procedures (National Research Council, 2012).

Teachers often use laboratory manuals to prepare labs since they suggest experiments associated with the unit's topic. For example, the College Board provided biology teachers with revised AP Biology lab manuals after the AP redesign (College Board, 2012). This lab manual encompasses 13 labs covering different topics such as artificial selection, cell division, biotechnology, and enzyme activity. The labs are aligned with the AP Biology curriculum and offer structured, guided, and open-inquiry learning opportunities. For example, students use onion cell samples and microscopes in a structured inquiry process to examine the mitosis and meiosis processes of cell division. To investigate artificial selection in a guided and open inquiry approach, students grow generations of Wisconsin Fast Plant, surveil the growth process and examine artificial selection based on their research questions.

Effectiveness of Inquiry Learning and Labs for Students

Inquiry activities can stimulate several cognitive processes among students, such as critical thinking and reasoning skills, self-regulation processes, and conceptual understanding and knowledge of the material (Anderson, 2002; Ben-Nun & Yarden, 2009; Chang et al., 2020; Nainmule & Corebima, 2018; Pedaste et al., 2012; Zion & Slezak, 2005) and gains in learning beliefs, self-efficacy, and performance (Lee et al., 2012; Nyutu et al., 2018; Şen et al., 2015).

In studies comparing traditional teaching approaches to inquiry learning and labs, knowledge gains and conceptual understanding are often significantly higher among students who perform inquiry learning activities compared to students who do not (Geier et al., 2008; Srisawasdi & Panjaburee, 2015; Taraban et al., 2007). For example, Geier et al. (2008) found that science content understanding and processing skills of 7th and 8th-grade students in Michigan who engaged in science inquiry activities were much higher than non-participating cohorts, as mirrored in higher test scores in a high-stakes statewide standardized assessment. Notably, higher test scores were found up to a year and a half after participation in inquiry learning, thus demonstrating that inquiry learning can lead to sustainable standardized achievement test gains.

The Teachers' Role During Inquiry Learning

The degree of teacher involvement during inquiry learning might differ depending on the complexity and form of inquiry activities and laboratory investigations (Zion & Mendelovici, 2012). The involvement includes supporting and guiding students in self-regulatory actions, helping them focus, and challenging and encouraging student learning (e.g., Taraban et al., 2007; Zion & Slezak, 2005). As these processes demand high levels of expertise and preparation, teachers often do not realize the full potential of inquiry labs (Wee et al., 2007). This might be a result of teachers not feeling sufficiently prepared to direct inquiry learning because they lack either the necessary pedagogical competencies (Glackin & Harrison, 2018) or they do not understand the affordances of inquiry learning for their students and have negative beliefs and attitudes regarding inquiry learning (Crawford, 2007). In response to educational reforms emphasizing this teaching method, teachers find incorporating more inquiry labs into their practice challenging because they lack experience with the revised curricula and exams (Fischer et al., 2018a).

Professional Development for Biology Teachers to Support Inquiry Learning

According to Desimone's conceptual framework of effective teacher PD, teachers who participate in PD programs can implement newly learned knowledge and skills or changed attitudes and beliefs into their classroom practice, from which students benefit and achieve higher learning outcomes and better grades (Desimone, 2009). Fishman et al. (2014) investigated how teachers' choice of PD during the AP Biology reform links with students' achievement and found that, although with only small effect sizes, specific patterns of PD participation influenced students' AP Biology exam scores. Furthermore, the study gave insights into an interplay between PD participation and the use of laboratory activities. Similar studies investigating the AP science redesigns showed that PD can help teachers align their instructional practice to curriculum reform (e.g., Fischer et al., 2018b; Hübner et al., 2021). An early study investigating the impact of PD during and after a state-wide science and mathematics reform in Ohio, United States, has shown that participating teachers showed a change in attitudes towards inquiry-based teaching strategies and their classroom use of inquiry-based instructional practices, resulting in sustained achievement gains (Supovitz et al., 2000).

Study Context

This study took place during the redesign of the AP Biology program in the United States. AP courses offer college-level instruction for high school students to help them prepare for college. When their AP exam scores are high enough (3 or above), students can use their exam scores to obtain college credit and skip introductory college courses (e.g., Atkinson & Geiser, 2009; Fischer et al., 2023; Geiser & Santelices, 2006). Prior research indicated that participation in the AP program was associated with higher college enrollment and graduation rates (Chajewski et al., 2011; Mattern et al., 2013).

Aligned with other national reforms like the NGSS, the College Board redesigned the AP Biology program in 2013. Teachers must now devote 25% of their classes to labs and conduct at least two labs per *Big Idea* (College Board, 2022b). The *Big Ideas* describe the course content across five essential and overarching biological concepts: evolution, energetics, information storage and transmission, and system interactions. These *Big Ideas* are a foundation for the course and can be found throughout different units. Certain aspects of these ideas can be explored through labs to facilitate an enduring conceptual understanding. The labs range from growing plants to understanding artificial selection and genetics to building computer models of mathematical principles like the Hardy-Weinberg formula (College Board, 2012). While many teachers started labs using structured and guided inquiry approaches, teachers may also decide to shift to a more open inquiry approach during the unit.

More than 191,000 students took the AP Biology exam in 2012 (College Board, 2012). Thus, the redesign also affected approximately 20,000 AP Biology teachers, who faced the challenge of implementing the revised curricula into their classroom practice. A manifold PD program was offered to all AP Biology teachers at no cost to support them in the reform implementation. For example, the College Board offered a six-hour online workshop focused on transitioning to inquiry-based learning labs with means to understand inquiry and its place in the classroom. Moreover, the College Board designed a website where teachers could access the AP Teacher Community and get help planning instructions and assessments from other teachers through a social blog. Notably, there was no requirement to enroll in PD to be able to teach AP courses. However, many teachers participate in the offered PD opportunities.

Research Questions

This study investigates how teachers adapted to the AP Biology redesign, focusing on implementing labs and inquiry learning activities. This study is situated at the intersection of inquiry learning and laboratory investigations, a nationwide science reform, and PD. Through longitudinal data from an extensive mandatory nationwide reform with high-stakes examinations, a large sample size, and precise analytical methods, we want to examine the nature of such reforms and give educational stakeholders, policymakers, researchers, and teachers insight into the challenges and practices associated with reform implementation. We aim to answer the following three research questions (RQs):

(RQ1) How did the number of implemented labs and inquiry labs change in the first three years following the AP Biology reform?

(RQ2) How did teachers' perceived labs-related challenges change in the first three years following the AP Biology reform?

(RQ3) How did participation in PD programs relate to the number of implemented labs, inquiry labs, and teachers' perceived labs-related challenges following the AP Biology reform?

Materials and Methods

Data Collection and Sample

This longitudinal study is connected to a National Science Foundation-funded project investigating teachers' responses to redesigning the AP program in the sciences. Data for this study were obtained through annual web-based surveys sent to all AP Biology teachers in the first three years after the AP Biology reform unless they had requested to be placed on the College Board's *do-not-contact* list.

This study focused on teachers who taught AP Biology in the first year after the redesign and responded to the survey in the first year. Thus, teachers who completed surveys in the following years but did not participate in the first year of the survey were excluded from our sample. This prior list-wise deletion was necessary to allow us to focus on teachers affected during the first year of the redesign, who all started with the same level of experience. Almost all the teachers were the only AP Biology teachers in their school (99.37%). To avoid having teachers nested within schools, twelve teachers who were not the only AP Biology teachers in their school were excluded from the sample. We included $N = 1{,}721$ AP Biology teachers in our dataset. In our sample, 28.15% of teachers were male, 71.85% female, and the majority were white (88.26%). The average number of years of teaching experience overall was 11.91 years ($SD = 4.71$), and the teachers had an average of 6.74 years ($SD = 4.72$) of prior AP Biology teaching experience. A non-response analysis indicated no significant bias (Appendix C).

Measures

Lab-related variables

To answer the first research question, teachers were asked to indicate the total number of labs completed during the current school year on a scale from 0 to 30. Similarly, to assess the number of completed inquiry labs, teachers indicated the number of student-generated inquiry investigations from the AP Biology Lab Guide during the school year on a scale from

0 to 13. Both items were treated as continuous. For a more detailed description of the data, see Supplementary Materials.

Teacher-level variables

To answer research question two, teachers were asked to rate different aspects of the AP Biology course in terms of perceived challenges. Teachers gave their responses on a 5-point Likert-type scale, with '1' indicating 'no challenge at all,' '3' indicating 'a moderate challenge,' and '5' indicating a large challenge. The items were treated as continuous variables. A latent challenges variable was constructed based on the three items asking teachers about inquiry-related challenges: 'perceived challenges: lab,' perceived challenges: inquiry labs', and 'perceived challenges: application of science practices to content.' An exploratory and confirmatory factor analysis confirmed strong factor loadings of the latent challenge factor, ranging between 0.6 and 0.8, with acceptable internal reliability for the first year (Cronbach's $\alpha = .74$), the second year (Cronbach's $\alpha = .74$) and the third year (Cronbach's $\alpha = .78$). To test for validity, we correlated the latent challenge factor for each year and got an acceptable correlation (challenges year one with challenges year two = .65; challenges year one with challenges year three = .62; challenges year two with challenges year three = .67).

In the descriptive analysis of our sample, we examined teachers' gender, ethnicity, years of experience teaching science, and years of experience teaching AP Biology.

To answer research question three, we examined teachers' reported PD participation at the beginning of the first year following the AP redesign. We focused on two PD activities provided by the College Board that centered on labs and inquiry labs: the one-day workshop 'Transitioning to Inquiry-based Learning' and the AP Teacher Online Community (APTC). In the survey, teachers indicated whether they had participated in the workshop the past year or in the APTC in preparation for working with the revised curriculum. Responses to the items were coded as binary variables, with '0' indicating no participation in the PD activity and '1' indicating participation. This led to one binary variable for each PD activity.

School-context variables

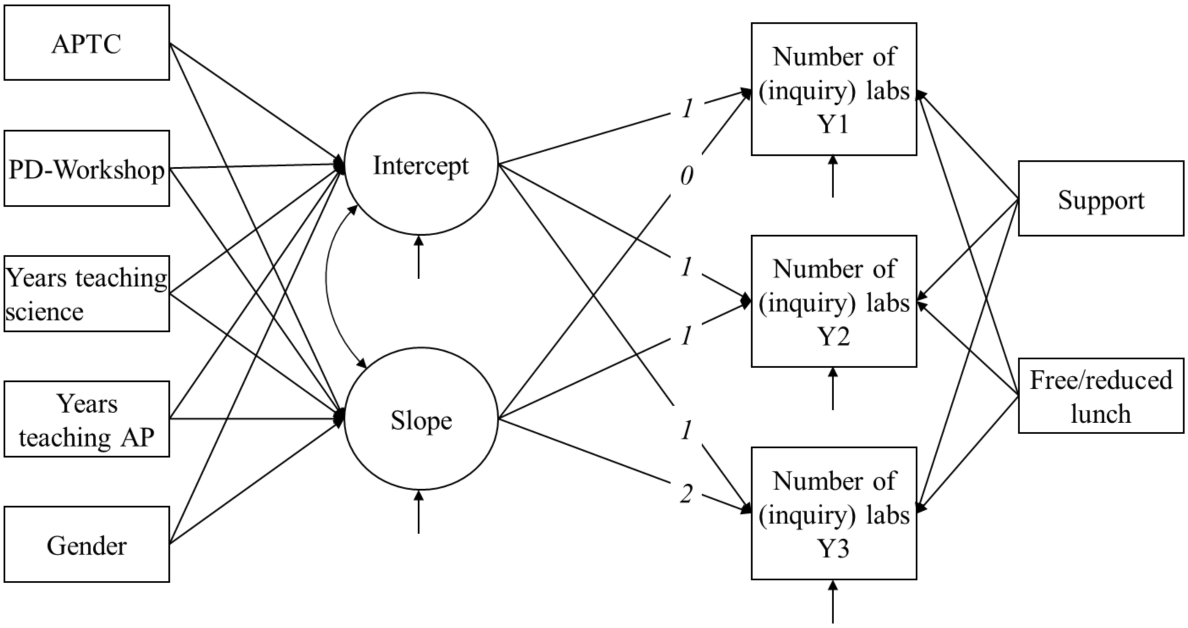
A composite variable was computed to describe teachers' perceived administrative support using exploratory and confirmatory factor analysis with Bartlett factor scores (DiStefano et al., 2009; Supplementary Materials S2). In addition to the teacher-specific variables collected through the annual surveys, the College Board provided school-level data, such as the number of students enrolled in free and reduced-price lunch programs. For each school, we calculated the percentage of students enrolled in these programs as an indicator of the school's overall socioeconomic status (SES), with fewer students enrolled indicating that the school had a higher overall SES, which might influence teacher preparedness, access to materials, and PD opportunities. Furthermore, we calculated the mean AP Biology scores, PSAT, and SAT scores among students in each school and used this information for the non-response analysis.

Analytical Methods

To answer RQ1, we applied first-order latent growth curve modeling (Grimm et al., 2016) to examine longitudinal growth in perceived challenges with labs and their implementation in classroom practice. This method is particularly well-suited for longitudinal data since it estimates inter-individual variability in the outcome variable across measurement occasions while accounting for differences in intraindividual trajectories over time (Grimm et al., 2016). All models were estimated with Mplus (Muthén & Muthén, 1998-2017) using full information maximum likelihood estimation for missing data (FIML; Graham, 2009; Enders, 2013). Growth curve models typically consist of two latent variables: intercept and linear growth/slope factors (see Figure 11). In line with common recommendations (Grimm et al., 2016; Muthén & Muthén, 1998-2017), the factor loadings of the intercept factor were set to '1.' The factor loadings of the latent slope factor were set to represent linear growth (0, 1, 2). To check for the model's validity, we included the standard model fit recommendations regarding CFI, TLI, and RMSEA (Hu & Bentler, 1999). The GCM was specified with the number of implemented labs as manifest continuous indicators and had an excellent model fit. A separate GCM was specified for the number of implemented inquiry labs with a good model fit (Figure 11).

Figure 11

Growth Curve Model to Investigate Changes in the Number of Labs and Inquiry Labs.

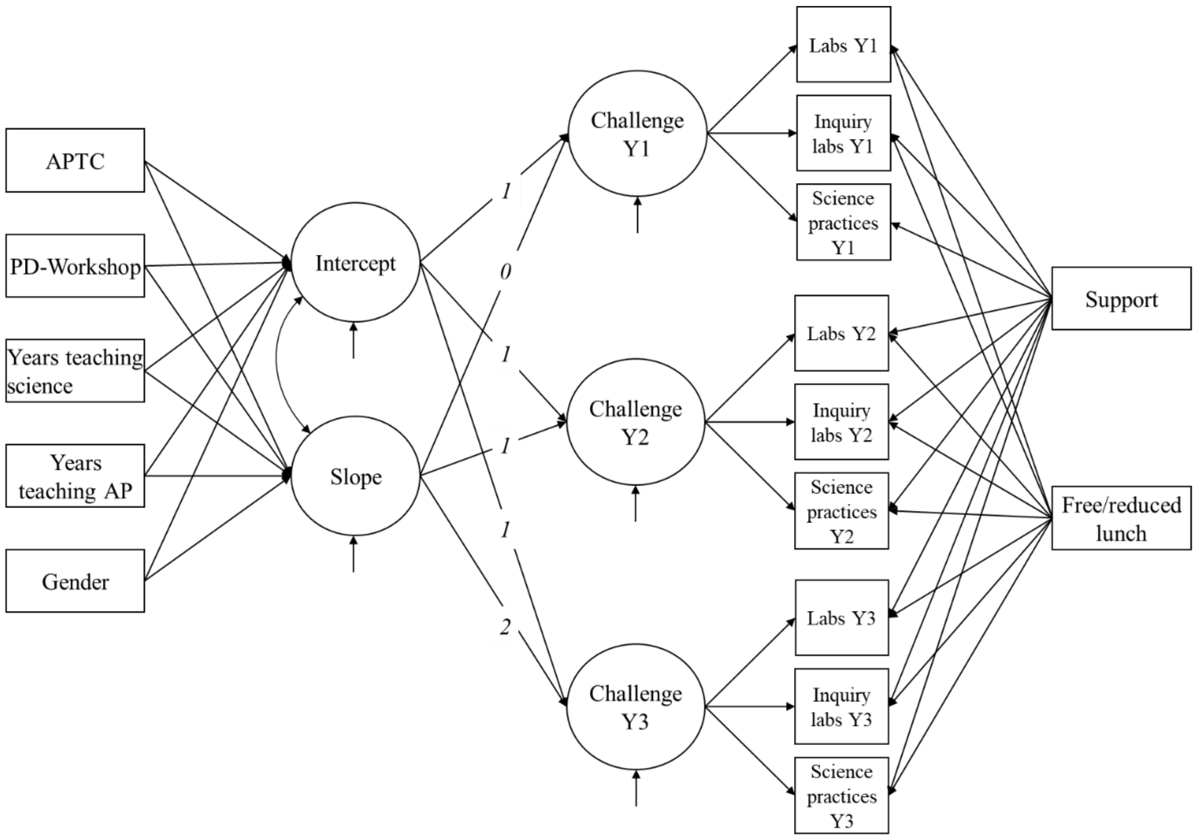


Note. Lines represent regressions; straight arrows represent residual variance; Y= year; method factors are not shown; correlations between covariates are not shown; residual variance of indicator items and covariates are not shown.

To answer RQ2, we specified a second-order GCM with one latent labs-related challenge factor for each of the three years (see Figure 12). When specifying the GCM for perceived labs-related challenges, a negative variance for the slope factor occurred (i.e., ‘Haywood case’), a common misspecification for GCMs (Chen et al., 2001; Zitzmann et al., 2022). Since the negative variance of the slope was not statistically significantly different from zero, we manually set the parameter to ‘0’. The measures of the model fit were highly satisfactory (Figure 12).

Figure 12

Growth Curve Model to Investigate Changes in Teachers' Perceived Labs-related Challenges.



Note. Lines represent regressions; straight arrows represent residual variance; Y= year; method factors are not shown; correlations between covariates are not shown; residual variance of indicator items and covariates are not shown.

To answer RQ3, we regressed participation in the workshop and APTC participation on the intercept and slope factors of the models from RQ1 and RQ2 to investigate whether participation in the workshop or APTC were associated with variation at the first measurement occasion and individual trajectories over time (see Figure 11 and 12).

Covariates

All models included several covariates. Covariates on the teacher level included teachers' gender, years of experience teaching science, years of experience teaching AP Biology, and perceived administrative support. On the school level, we included the percentage of students enrolled in the free and reduced-price lunch programs.

Results

Number of Implemented Labs and Inquiry Labs

To answer RQ1, we examined the number of labs and inquiry labs the teachers had implemented in the first three years after the AP Biology redesign. In the first year after the AP redesign, the teachers implemented an average of 13.84 labs (SD = 5.54) into classroom practice, of which 3.5 (SD = 2.81) were inquiry labs. In the second year, teachers conducted 14.25 (SD = 5.44) labs and 4.73 (SD = 2.92) inquiry labs. The average number of labs in the third year was 15.11 (SD = 6.13), of which 4.89 (SD = 2.94) were inquiry labs. Latent growth curve models indicated positive growth for both the overall number of labs ($\beta = 0.58$, $p < .001$) and the number of inquiry labs ($\beta = 0.97$, $p < .001$). Table 6 provides a complete description of the results.

Table 6

Results of Growth Curve Models

Model	*Number of Implemented Labs*		*Number of Implemented Inquiry Labs*		*Perceived Labs-Related Challenges*	
	Estimate (*S.E*)	*p*-value	Estimate (*S.E*)	*p*-value	Estimate (*S.E*)	*p*-value
Means						
Intercept	**13.151 (0.405)**	**<.001**	**3.071 (0.217)**	**<.001**	**3.564 (0.055)**	**<.001**
Slope	**0.579 (0.191)**	**.002**	**0.969 (0.138)**	**<.001**	**-0.195 (0.049)**	**<.001**
Variances						
Intercept	**23.215 (1.718)**	**<.001**	**7.601 (0.407)**	**<.001**	**0.695 (0.061)**	**<.001**
Slope	1.344 (0.696)	.053	**1.800 (0.172)**	**<.001**	0.000 (0.000)	.000
Correlation						
Intercept with Slope	-0.123 (0.139)	.377	**-0.570 (0.037)**	**<.001**	0.004 (0.027)	.870
Intercept						
PD participation						
PD-Workshop	**2.029 (0.587)**	**.001**	**0.697 (0.315)**	**.027**	-0.086 (-0.084)	.301
APTC	0.644 (0.436)	.140	**0.614 (0.234)**	**.009**	-0.046 (0.060)	.442
Control variables						
Years of teaching science	**0.186 (0.056)**	**.001**	0.035 (1.406)	.160	-0.007 (0.008)	.379
Years of teaching AP science	**0.187 (0.047)**	**<.001**	-0.007 (-0.241)	.810	-0.008 (0.007)	.210
Gender, female	**-1.088 (0.462)**	**.018**	**-0.519 (0.246)**	**.035**	-0.084 (0.063)	.185
Slope						
PD participation						
PD-workshop	0.168 (0.262)	.521	0.270 (0.188)	.151	0.023 (0.067)	.728
APTC	-0.117 (0.202)	.564	-0.218 (0.145)	.132	0.009 (0.053)	.861
Control variables						
Years of teaching science	-0.058 (0.026)	.026	-0.003 (0.015)	.825	-0.007 (0.007)	.310
Years of teaching AP science	-0.012 (0.021)	.564	-0.003 (0.019)	.855	-0.001 (0.005)	.858
Gender, female	0.064 (0.210)	.760	0.018 (0.151)	.905	**0.137 (0.054)**	**.012**
Control variables on challenge year 1						

Administrative support	0.080 (0.185)	.666	0.016 (0.124)	.898	**-0.215 (0.040)**	**<.001**
Percent free or reduced lunch	-0.003 (0.009)	.749	-0.005 (0.005)	.317	0.001 (0.001)	.404
Control variables on challenge year 2						
Administrative support	0.282 (0.177)	.110	0.124 (0.123)	.310	-0.039 (0.051)	.449
Percent free or reduced lunch	-0.002 (0.008)	.794	**-0.010 (0.005)**	**.034**	0.002 (0.002)	.344
Control variables on challenge year 3						
Administrative support	0.310 (0.290)	.285	0.022 (0.180)	.902	-0.092 (0.066)	.163
Percent free or reduced lunch	0.002 (0.011)	.865	-0.011 (0.006)	.066	0.000 (0.002)	.831
Comparative Fit Index (CFI)	0.998		0.921		0.975	
Tucker-Lewis Index (TLI)	0.997		0.850		0.968	
RMSEA	0.008		0.042		0.021	
SRMR	0.019		0.020		0.028	
χ^2 (df)	1431.33(36)	<.001	759.84(36)	<.001	3283.76 (135)	<.001

Note. PD-workshop = 1-day workshop "Transitioning to Inquiry-based Learning"; APTC = online AP teacher community; RMSEA = root mean square error of approximation; SRMR = standardized root mean square residual. Bold values indicate significance.

The correlation between the intercept and the slope factor for the number of implemented labs was not significant. This implies that both teachers who implemented a high and a low number of labs in year one exhibited a similar increase in the number of labs over time. However, the correlation between the intercept and slope for inquiry labs was negative, $r = -.57$, $p < .001$, indicating that teachers who implemented a high number of inquiry labs in year one showed a decrease in inquiry labs over time. In contrast, teachers who implemented a lower number of inquiry labs increased their number of inquiry labs over time. The variances of the intercept of the number of implemented labs ($\beta = 23.22$, $p < .001$) and inquiry labs ($\beta = 7.60$, $p < .001$) were significant, which reveals inter-individual differences in the number of implemented labs and inquiry labs at the first time point. Additionally, the variance of the slope factor for implemented inquiry labs was significant ($\beta = 1.8$, $p < .001$). In contrast, the variance of the slope for the overall number of implemented labs was not significant, indicating that teachers show inter-individual differences in the growth trajectories of their number of inquiry labs over time. Furthermore, the models suggest that years of prior teaching science experience significantly impacted the number of implemented labs ($\beta = 0.17$, $p = .001$), with one additional year of experience teaching science resulting in an average increase of 0.19 labs. Similarly, prior AP Biology teaching experience was associated with more implemented labs in the first year after the reform ($\beta = 0.19$, $p < .001$). Interestingly, female teachers implemented fewer labs in the first year than male colleagues ($\beta = -1.09$, $p = .018$). For inquiry labs, gender also significantly impacted the number of implemented labs ($\beta = -0.52$, $p = .035$). Furthermore, the SES of the schools slightly influenced the implementation of inquiry labs during the second year of the reform, with a one percentage point higher share of students enrolled in the free and reduced-price lunch program leading to $\beta = -0.01$ ($p = .034$) fewer implemented inquiry labs.

Perceived Labs-Related Challenges

To answer the second research question, we examined how teachers perceived the challenge of implementing lab-related features of the AP Biology curriculum redesign into their classroom practice. Descriptively, teachers perceived labs-related challenges ($M = 3.56$, $SD = 0.06$) as a moderate challenge in the first year following the AP redesign ($M = 3.12$, $SD = 1.81$), the second year ($M = 3.04$, $SD = 0.88$) as well as in the third year ($M = 2.8$, $SD = 0.91$). Latent growth curve models indicated a negative growth rate for teachers' perceived lab-related challenges ($\beta = -0.19$, $p < .001.$). Table 6 provides a complete description of the results. The correlation between the intercept and slope factor was not significant ($r = .004$, $p = .87$), indicating that the initial level was unrelated to the growth rate. The intercept variance ($\beta = 0.69$, $p <.001$) was significant, suggesting inter-individual differences in perceived challenges during the first year following the AP redesign. The variance of the slope was not significant, implying that teachers starting with different scores in year one experienced a similar decrease in perceived challenges in the three years after the AP redesign. Notably, perceived administrative support during the first year of implementation had a significant influence on teachers' level of perceived challenges related to reform, indicating that more administrative support led teachers to perceive fewer challenges during the first year ($\beta = -0.22$, $p <.001$), but this did not hold for the following years, as it is evident by the non-significant slope.

The Influence of PD Participation on Implemented Labs and Perceived Challenges

To investigate whether PD participation had a significant impact on the initial values of the number of implemented labs, inquiry labs, and perceived challenges and whether it influenced growth over the three years following the reform (RQ3), we regressed the dichotomous variables for PD participation in the first year after the redesign on the intercept and slope factors. Teachers who participated in the 1-day workshop implemented, on average, a higher number of labs ($\beta = 2.03$, $p = .001$) and inquiry labs ($\beta = 0.69$, $p = .027$) during the first year after the redesign than teachers who did not participate in the workshop (Table 6). Participation in the APTC was only related to a significant increase in the implementation of inquiry labs during the first year ($\beta = 0.61$, $p = .009$). This result indicates that participation in inquiry-focused PD activities before the start of the school year was beneficial for teachers in the first year of the AP redesign and might have encouraged them to implement more labs into their classroom practice. The associations with the intercept can be interpreted as immediate effects of PD participation since the PD activities took place before the first survey. Thus, PD participation can immediately affect the implementation of labs. The insignificant effect on the growth rate suggests that although there were immediate associations at year one, teachers did not continue implementing more labs to respond to their PD participation over the years.

There were no significant associations between PD participation on perceived labs-related challenges (Table 6), suggesting that PD participation did not have an immediate or long-term effect on teachers' perceived challenges.

Discussion

This longitudinal study aimed to identify changes in the number of implemented (inquiry) and labs-related challenges following the nationwide AP Biology curriculum redesign in the United States. Furthermore, the study examines whether prior participation in PD activities benefited the number of implemented (inquiry) labs and perceived labs-related challenges. This study extends prior research on the AP curricular redesign by investigating its implications for (inquiry) labs in biology, which has not yet been examined. The two main results of the study can be summarized as follows: First, teachers' perceived labs-related challenges decreased over three years, while the number of (inquiry) labs increased. Second, prior PD participation has a positive effect since teachers reported more (inquiry) labs in the first year.

Regarding the first finding, although teachers could implement an increasing number of labs over the three years, teachers did not start with the same number of labs, as indicated by the high variance in the GCM. This shows that some teachers could meet the requirements of the redesigned AP curriculum in the first year, while others might have struggled for different reasons. A reason suggested by prior literature might be low self-efficacy regarding instructional practices. For example, Cerit (2013) found that teachers' willingness to implement educational reforms significantly correlates with their self-efficacy regarding instructional strategies. Furthermore, teachers who struggled with implementing the reform might not have participated in PD, as a lack of guidance can be attributed to limited changes in classroom practice (Margot & Kettler, 2019). However, the positive slope and its insignificant variance imply that all teachers, irrespective of their starting values, were able to integrate more labs and inquiry labs into their practice over the three years following the reform. This might be due to the importance of AP exams since scores can be used for college enrollment and credit (Chajeswki et al., 2011; Mattern et al., 2013). Typically, reform efforts take longer to be implemented. Therefore, teachers might feel more pressure to implement reform-related changes in their classroom practice to ensure their students are prepared for the AP Biology exam. Similarly, in a study by Geier (2008), teachers were able to strengthen their use of reform-based curricular material in their second and third years using the revised curriculum, suggesting that each time a teacher makes use of revised materials or practices, it strengthens their understanding of how to teach the redesigned unit. Interestingly, previous research found a similar pattern for implementing labs in the context of the AP Chemistry curriculum redesign (Fischer et al., 2018a). Teachers implemented more labs one year following the AP Chemistry redesign, while other classroom practices did not significantly increase. Additionally, perceived challenges significantly decreased after a year of implementation, indicating that teachers' challenges decreased as they gained experience implementing the curriculum. This decline in perceived challenges was also evident in this study, where teachers who started at different initial values in year one exhibited a similar decline in their labs-related perceived challenges, indicating that gaining experience with the practical implementation of the reform might be a key factor for perceiving fewer challenges (Hall et al., 2015). This might also align with the CBAM, which states that teachers have innate concerns when faced with innovation and might shift over time (Fischer et al., 2018a; Charalambous & Philippou, 2010).

When examining the influence of PD participation, teachers who participated in the AP Biology workshop 'Transitioning to Inquiry-based Labs' implemented more labs during the first year. However, participation in this PD did not significantly help teachers implement more inquiry labs, even though the workshop was designed to help teachers modify their lab routines to incorporate more inquiry learning opportunities for their students. However, we cannot rule out that teachers who had already implemented many labs and inquiry labs were more likely to participate in the workshop. Research has shown that teacher characteristics influence teachers' perception of PD and ability to deploy the learned content and knowledge in their classroom practice. For example, Jones and Eick (2007) showed that teachers with low content knowledge benefitted from PD, in which they provided structures for implementing inquiry in the classroom.

As for APTC participation, a prior study by Frumin et al. (2018) investigated teachers' participation in the APTC during the AP Chemistry, Physics, and Biology reforms. The results indicated that teachers with more experience were significantly more likely to participate in the APTC and during the first years after the redesign if they found the reform more challenging. The study also found an association between APTC use and AP science scores across all disciplines, indicating that the teachers who participated in the APTC taught students who scored higher in the AP exams. The authors argued that the APTC offered additional opportunities for teachers that exceeded the other PD activities offered by the College Board. Participants often highlighted the ability to post individualized questions and content and be part of a shared affective community. In accordance with our results, the ability to post one's individual questions regarding inquiry labs in the APTC might have helped teachers implement more inquiry teaching by allowing them to share resources, tips, and experiences with their colleagues, in contrast to participating in the theory-driven workshop 'Transitioning to Inquiry-based Labs.' An explanation of why the APTC was more successful than the one-day workshop might be that it employed many core features of successful PD: coherence, content focus, duration, active learning, and collaborative participation. Studies investigating the use of teacher online communities during the NGSS reform have also indicated a positive effect for teachers who participated, as they were more successful in negotiating the meaning of the NGSS reform and its redesigned curriculum (Friedrichsen & Barnett, 2018).

Together with previous research (e.g., Fischer et al., 2018b; Grigg et al., 2013; Hübner et al., 2021), this study suggests that attending personalized PD opportunities with a longer duration and frequent participation in the early stages of educational reforms can be beneficial for teachers and might help them to better implement core features of educational reforms in their classroom practice.

Appendix

A1

A non-response analysis with nonparametric Mann-Whitney U tests indicated that teachers in our sample taught in schools with slightly higher average AP scores (year one, $z = 12.73$, $p < .001$, $r = .14$; year two, $z = 12.87$, $p < .001$, $r = .14$; year three, $z = 11.41$, $p < .001$, $r = .12$), slightly higher average PSAT scores (year one, $z = 9.13$, $p < .001$, $r = .10$; year two, $z = 24.29$, $p < .001$, $r = .25$; year three, $z = 22.60$, $p < .001$, $r = .23$), slightly higher SAT scores (year one, $z = 8.28$, $p < .001$, $r = .09$; year two, $z = 20.05$, $p < .001$, $r = .22$; year three, $z = 17.64$, $p < .001$, $r = .19$), and slightly lower enrollment rates in free or reduced-price lunch programs (year one, $z = 8.88$, $p < .001$, $r = .101$; year two, $z = 7.33$, $p < .001$, $r = .08$; year three, $z = 7.24$, $p < .001$, $r = .08$) compared to the overall AP Biology population. However, due to the small effect size ($r \approx .1$ to $.25$), our sample can still be considered a good representation of the overall AP Biology teacher population.

A2

Survey questions and answer choices included in web-based surveys

Demographic data

Are you male or female?
- Male
- Female

What is your race? (Mark all that apply):
- American Indian or Alaska Native
- Asian
- Black or African American
- Native Hawaiian or Other Pacific Islander
- White

Degree: What is your highest degree completed?
- Associate's Degree
- Bachelor's Degree
- Master's Degree
- Certificate of Advanced Study
- Doctoral Degree

Teaching experience

Approximately how many years have you taught **HIGH SCHOOL SCIENCE** (not including this year)? (Pull down menu)

- 0 years (This is the first year I’ve taught high school science)
- 1 years
- 2 years
- …
- More than 50 years

- Approximately how many years have you taught **AP BIOLOGY** (not including this year)? (Pull down menu)
- 0 years (This is my first year teaching AP Biology)
- 1 years
- 2 years
- ….
- More than 50 years

Perceived challenges for latent challenge factor

In the current school year, the AP redesign may have posed challenges to your instruction. Please indicate below how much of a challenge each of the following elements of the AP redesign was for you. (Reminder: Nobody from the College Board will have access to your individual responses to this or any other question in this survey.) [5-point Likert scale item: 1 - No challenge at all, 3 - A moderate challenge, 5 - A large challenge]

- Biology content
- The organization of Biology content
- Labs
- Inquiry Labs
- Format of questions/problems/exam
- Application of science practices to the content
- Development of a new syllabus
- Understanding the "boundary statements"
- Designing new student assessments
- Using the textbook for the Biology AP redesign
- Working with a new or different textbook
- The pacing of my course
- Moving my students to a conceptual understanding of Biology
-

Laboratory Investigations

Approximately how many lab investigations in total did your students complete this year?

- o none
- o 1 lab investigation
- o 2 lab investigations
- o ….
- o More than 25 lab investigations

The labs in the AP Biology Lab Guide have a major section having to do with skills development and a final few pages that have to do with using those skills to perform a "student-generated" investigation.

- o How many of your labs included a student-designed investigation?
- o none
- o 1 lab investigation
- o 2 lab investigations
- o ….
- o 13 lab investigations

PD participation

There are many different ways that teachers might prepare for teaching AP science. Below, please indicate which of the following resources, informal professional development (PD) activities, or formal PD activities you used as part of your preparation to teach the revised AP curriculum within the past year.

AP Biology: Transitioning to Inquiry-Based Labs (1 day)
This College Board sponsored in person (face-to-face) workshop provides AP Biology teachers with a means to understand inquiry and its place in the classroom.

- o I was unaware of this opportunity
- o I was aware but did not participate in the past year
- o I participated in this PD in the past year
- o I led this PD in the past year

Self-Paced Online Course: Transitioning to Inquiry-Based Labs (5-6 hours)
This College Board sponsored online course provides AP Biology teachers with a means to understand inquiry and its place in the classroom, including models of inquiry and inquiry levels.

- o I was unaware of this opportunity
- o I was aware but did not participate in the past year
- o I participated in this PD in the past year
- o I led this PD in the past year

College Board Web Site: The AP Teacher Community
For the purpose of this study, we consider the online AP Teacher Community (https://apcommunity.collegeboard.org/web/apbiology/) as a form of professional development if you accessed the online AP Teacher Community to help in your planning of instruction and/or assessment, whether you posted to the site or not.

- o I was unaware of this opportunity
- o I was aware but did not participate in the past year
- o I participated in this PD in the past year

○ I led this PD in the past year

Supplemental Material

S1

The scale teachers used to indicate the number of labs and inquiry labs in year one of the surveys deviated slightly. The first-year survey asked teachers to indicate the numbers of implemented labs on an ordinal scale (i.e., 1 = between 0 and 2; 2 = between 3 and 5; 3 = between 6 and 7; 4 = between 8 and 10; 5 = more than 10), while the survey in the other years contained a continuous scale ranging from 0 to more than 35 labs. Moreover, the ordinal data were highly skewed towards the last category, with -1.61 skewness, making it difficult to disassemble effects within the last category since the last category, '5= more than 10', is an open-ended question and not specific enough. Therefore, we used the retrospective answers from the second-year survey to compare the answers between years. Here, teachers had to indicate the number of implemented labs and inquiry labs in the first year after the reform on a continuous scale. According to other study designs, using retrospective answers might lead to less response shift bias (e.g., Bhanji et al., 2012; Drennen & Hyde, 2008). Furthermore, continuous scales are more desirable to use over ordinal scales, as arithmetic calculations are more interpretable (Stevens, 1946). We computed Spearman's correlation between the original ordinal and retrospective categorical answers to compare the responses from year one with the retrospective responses from year two. The correlation was $r = .55$ for labs and $r = .52$ for inquiry labs, indicating a moderate correlation. Therefore, we analyzed the number of labs and inquiry labs for year one of the reform with the retrospective answers from the year two survey.

S2

Similar to previous studies (Fischer et al., 2018a, Fischer et al., 2018b, Frumin et al., 2018), teachers' perceived administrative support encompassed teachers' responses to the following items: (a) 'Principal has an understanding of how challenging AP science is for students,' (b) 'Principal has an understanding of the challenges of AP science teaching,' (c) 'Principal is supportive of teacher PD participation,' (d) 'lighter teaching load is offered,' (e) 'fewer out-of-class responsibilities are assigned,' and (f) 'additional funding is provided.' The reliability was computed with Cronbach's alpha and was satisfactory ($\alpha = 0.71$), with satisfactory factor loading from .2 to .9.

Table S3

Measures Used for Research Questions 1-3

Name	Description	Variable Type
	Research Question 1	
prior_labs_2014	The number of labs teachers implemented in the school year of the first year of the AP redesign	Continuous
labs_2014	The number of labs teachers implemented in the school year of the second year of the AP redesign	Continuous
labs_2015	The number of labs teachers implemented in the school year of the third year of the AP redesign	Continuous
	Research Question 2	
Challenge_1 Challenge_2 Challenge_3	Labs Inquiry labs Science content to practice	Continuous: 1 = No challenge at all, 5 = A large challenge
	Research Question 3	
PD_workshop	1-day workshop "Transitioning to Inquiry-based Learning"	Dichotomous: 0 = no participation, 1 = participation
PD_APTC	AP teacher online community	
	Control Variables	
Administrative support	Teachers perceived administrative support in the first year of the redesign	Continuous: 1 = no support, 5 = A high support
Free/reduced lunch program	Percentage of students in a school which are enrolled in a free or reduced lunch program	Continuous
Years of teaching science	The years of experience teaching science in the first year of the AP redesign	Continuous
Years of teaching AP science	The years of experience teaching AP science in the first year of the AP redesign	Continuous
Gender	Teachers gender	Dichotomous: 0 = male, 1 = female

S4

Methods Supplement. Mplus Code

```
TITLE: Teachers’ number of laboratory investigations with covariates centered at the
grandmean;
DATA: FILE = “Path”;
VARIABLE:
NAMES = VAR NAMES (not displayed for the sake of clarity);
MISSING=.;
define: center yap_13 ysci_13 persl_13 persl_14 persl_15
cprin_13 cprin_14 cprin_15(grandmean);
model:
interc by plab1_14-lab1_15@1;
linear by plab1_14@0 lab1_14@1 lab1_15@2;
[plab1_14 - lab1_15@0 interc linear];
interc with linear;
interc on dgender fpd3_13 ocomm_13 yap_13 ysci_13;
linear on dgender fpd3_13 ocomm_13 yap_13 ysci_13;
plab1_14 on cprin_13 persl_13;
lab1_14 on cprin_14 persl_14;
lab1_15 on cprin_15 persl_15;
dgender fpd3_13 ocomm_13 yap_13 ysci_13 with
dgender fpd3_13 ocomm_13 yap_13 ysci_13;
cprin_13 cprin_14 cprin_15 persl_13 persl_14 persl_15 with
cprin_13 cprin_14 cprin_15 persl_13 persl_14 persl_15;
cprin_13 cprin_14 cprin_15 persl_13 persl_14 persl_15 with
dgender fpd3_13 ocomm_13 yap_13 ysci_13;
```

```
TITLE: Teachers' number of inquiry laboratory investigations with covariates centered at the
grandmean;
DATA: FILE = "Path";
VARIABLE:
NAMES = VAR NAMES (not displayed for the sake of clarity);
MISSING=.;
define: center yap_13 ysci_13 persl_13 persl_14 persl_15
cprin_13 cprin_14 cprin_15(grandmean);
model:
interc by plab3_14-lab3_15@1;
linear by plab3_14@0 lab3_14@1 lab3_15@2;
[plab3_14 - lab3_15@0 interc linear];
plab3_14@0;
interc with linear;
interc on dgender fpd3_13 ocomm_13 yap_13 ysci_13;
linear on dgender fpd3_13 ocomm_13 yap_13 ysci_13;
plab3_14 on cprin_13 persl_13;
lab3_14 on cprin_14 persl_14;
lab3_15 on cprin_15 persl_15;
dgender fpd3_13 ocomm_13 yap_13 ysci_13 with
dgender fpd3_13 ocomm_13 yap_13 ysci_13;
cprin_13 cprin_14 cprin_15 persl_13 persl_14 persl_15 with
cprin_13 cprin_14 cprin_15 persl_13 persl_14 persl_15;
cprin_13 cprin_14 cprin_15 persl_13 persl_14 persl_15 with
dgender fpd3_13 ocomm_13 yap_13 ysci_13;
```

```
TITLE: Teachers' perceived challenges with covariates centered at the grandmean;
DATA: FILE = "Path";
VARIABLE:
NAMES = VAR NAMES (not displayed for the sake of clarity);
MISSING=.;
define: center yap_13 ysci_13 persl_13 persl_14 persl_15
cprin_13 cprin_14 cprin_15(grandmean);
model:
ch_13 by c4_13
        c3_13 (l1)
        c6_13 (l2);
ch_14 by c4_14
        c3_14 (l1)
        c6_14 (l2);
ch_15 by c4_15
        c3_15 (l1)
        c6_15 (l2);
[c4_13@0 c4_14@0 c4_15@0];
[c3_13 c3_14 c3_15] (1);
[c6_13 c6_14 c6_15] (2);
is3 by c3_13 c3_14@1 c3_15@1;
is6 by c6_13 c6_14@1 c6_15@1;
model: interc by ch_13-ch_15@1;
      linear by ch_13@0 ch_14@1 ch_15@2;
[ch_13 - ch_15@0 interc linear];
linear@0;
interc with linear;
interc on dgender fpd3_13 ocomm_13 yap_13 ysci_13;
linear on dgender fpd3_13 ocomm_13 yap_13 ysci_13;
ch_13 on cprin_13 persl_13;
ch_14 on cprin_14 persl_14;
ch_15 on cprin_15 persl_15;
dgender fpd3_13 ocomm_13 yap_13 ysci_13 with
dgender fpd3_13 ocomm_13 yap_13 ysci_13;
```

```
cprin_13 cprin_14 cprin_15 persl_13 persl_14 persl_15 with
cprin_13 cprin_14 cprin_15 persl_13 persl_14 persl_15;
cprin_13 cprin_14 cprin_15 persl_13 persl_14 persl_15 with
dgender fpd3_13 ocomm_13 yap_13 ysci_13;
is3 with ch_13-ch_15@0 interc@0 linear@0 dgender-cprin_15@0;
is6 with ch_13-ch_15@0 interc@0 linear@0 dgender-cprin_15@0;
```

S5

Limitations

This study has several limitations that mainly stem from the data source. Since the data relied on self-reports from teachers, threats to validity cannot be excluded. However, research states that self-reports are often a reliable measure that, together with advantages like time efficiency and feasibility of data collection, is widely used and robust (e.g., Clunies-Ross et al., 2008; Koziol & Burns, 1986). Furthermore, all questions were first piloted with experienced teachers using cognitive interviews (e.g., Desimone & Carlson Le Floch, 2004; Fischer et al., 2018; Fishman et al., 2014). The interviews validated the vocabulary and scales used in the self-report questionnaires. Similar approaches have been used in similar research studies (e.g., Glynn et al., 2009; Karabenick et al., 2007).

Notably, the number of reported labs in the first year of implementation was assessed retrospectively, which runs the risk of introducing measurement error since the correlation between the initial answers in the year one survey and the retrospective answers in the year two survey was also only moderate. Moreover, the web-based survey might have introduced measurement errors related to the survey respondents and the survey instrument. Our non-response analysis found that the data might be slightly biased toward teachers who can implement the AP curriculum more successfully and thus prepare their students better for the AP exams, which shows in their students' higher AP Biology exam scores. Furthermore, the teachers were from schools in which fewer students were enrolled in free and reduced-price lunch programs than the overall AP Biology population, indicating that these schools were in districts with overall higher SES and possibly better equipped than other schools, which might also be reflected in the students higher PSAT and SAT scores.

Importantly, our findings are correlational, so we caution against a causal interpretation of the data.

S6

Implications

This study contributes to biology education and educational reform research in many ways. First, the context of the AP redesign, a top-down, nationwide mandated curriculum and exam reform, gave us a unique opportunity to investigate how teachers perceive the challenge of implementing more labs and inquiry learning, which were the core features of the reform. The study context is particularly interesting since the redesign affects a high number of teachers (approximately 20,000) and students (more than 190,000 per year). The results might generalize to other large-scale curriculum reforms in the STEM field involving the implementation of regular labs, such as physics or chemistry. Given our results, teachers and educational stakeholders such as school principals should be optimistic that core features of educational reforms can be implemented over time, even though the increase might be slow but steady. In the case of AP Biology, the number of labs and inquiry labs increased over the years, while perceived challenges with labs and inquiry labs decreased over time. However, future research might examine why some teachers were more successful in implementing more labs and inquiry learning in the first year of the redesign and which specific teacher characteristics have contributed to this pattern. Furthermore, our results also imply that participation in inquiry-focused PD before the initial implementation of redesigned curricula and exams had some short-term effects and might have helped some, but not all, teachers during the initial year. Importantly, these associations were not seen in the long term. Future research might be needed to investigate what PD features lead to improved teacher outcomes.

In summary, our results might encourage PD providers and educational stakeholders to either provide more extended PD activities spanning the first months or even years of educational reform or to provide more specific and personalised PD activities like online forums or mentors to help teachers address specific questions and problems, leading to fewer perceived challenges and more significant implementation of core features of reforms. Teachers might also be encouraged to participate in more PD, especially in areas with particular difficulties.

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Study 3

Morina, F., Fütterer, T., Rosenberg, J., Caprenter, J., & Fischer, C. (2024). *Unlocking the Potential of Educational Resources: An Examination of Sharing and Usage Patterns in Educational Online Communities.* Manuscript in Preparation

Abstract

X (formerly known as *Twitter*) has, for more than a decade, been an important site for teachers' collaboration and informal professional learning. Prior research has suggested that teachers primarily use X to share and acquire educational resources (ER) like lesson materials or open educational resources (OER). However, whether teachers report implementing these materials into classroom practice is under-studied. Therefore, this study investigates how teachers in four German hashtag community types report their implementation of ER through qualitative and quantitative analyses. Our sample comprises 2,064,799 posts (formerly known as *tweets*) from 116,967 users. The results suggest that ER, in the form of links and media types, are not shared equally among the community types. Furthermore, the sentiment of replies to posts that contain resources is generally positive. Around 2.2% to 3.1% of replies to posts with ER indicate usage in the classroom. Resources shared by influential teachers are statistically significantly more positive in sentiment, and the intention to use the resources is higher than for other user characteristics. This study advances educational research on informal learning opportunities for teachers via social media. It informs stakeholders about the possibilities social media platforms may offer as places to acquire ER.

Keywords: Teacher Professional Development, Social Media, Informal Learning, Learning Communities, Data Science Applications in Education

Introduction

Teachers rely on various materials and resources for everyday teaching (Brown, 2011). Resources can include tangible objects like texts, lesson plans, or lab manuals, as well as techniques or tools that can be used to effectively convey content knowledge to students (Kimmons, 2015). Working with resources is essential for student and teacher learning, as materials influence what teachers do during their practice (Brown, 2011). For instance, curriculum material or textbooks influence and guide teachers in deciding what content to teach in class (e.g., Davis et al., 2016; Lloyd & Remillard, 2011). Typically, teachers learn the skills to find, adapt, and work with curriculum material or textbooks during their education in university, internships, and their time as pre-service teachers (Kim & Tan, 2011; Ruys et al., 2012). However, with physical curriculum material or textbooks, such resources can quickly become outdated or unsuitable for the learning dynamics within a class or working with a particular group of students. A lack of material, outdated material, or material received not in time can dissatisfy teachers with their teaching (Marable & Raimondi, 2007). To conquer dissatisfaction and to be better prepared for their teaching, many teachers rely on their professional network to receive more up-to-date and individualized resources from their community by asking trusted colleagues (Macià & García, 2016) or searching online for educational resources (ER).

ER vary from simple pictures of lesson plans for specific topics to elaborated online courses for more profound professional development (Hylén, 2006; Olivier & Rambow, 2023) and include teaching materials, content modules, learning objects, collections, journals, courses, and tools like software, content, and learning management systems. ERs can be acquired through official websites and repositories of ER or, more informally, through social media. In recent years, many teachers have been turning to social media to acquire resources and to participate in informal learning and professional development (Greenhow et al., 2018). In particular, X is popular among teachers as an effective outlet to get personalized and just-in-time responses from their colleagues (Fütterer et al., 2021). Prior research suggests X as an effective venue for acquiring teaching materials and getting ideas and feedback for classroom practice (Carpenter, 2015; Fischer et al., 2019; Rosenberg et al., 2020; Wesely, 2013) and that a primary reason for teachers to use X is to acquire materials and resources (Carpenter, 2015; Carpenter & Krutka, 2014; Fütterer et al., 2021). However, there is limited large-scale empirical evidence regarding teachers' use of resources they have found on X in their classroom practice.

Therefore, based on 2,064,799 posts in four teacher communities, this study evaluates the patterns of how and where ER are shared and how the teacher communities on X perceive them. Moreover, according to the Theory of Planned Behavior (TPB; Ajzen, 1991), where intentions are postulated as strong predictors for behavior, we aim to find the intention of teachers to use ER in the teachers' classroom practice using big data analyses. Finally, we investigate how user characteristics are associated with the perception of ER and whether more positive perceptions might be associated with usage. This study is one of the few to investigate X on the level of reported implementation of resources from the platform into classroom practice.

Literature Review

Educational Resources and Materials

Teachers can face barriers to acquiring traditional teaching materials, like textbooks or lab manuals. For example, textbook acquisition for teachers in the United States is tied to the school districts in which they teach. Institutions typically purchase textbooks on behalf of the students, but as they are costly, they are purchased for a long cycle, which might extend to ten years or longer in many schools (FCC, 2012). Thus, access to teaching materials is often restricted and copy-righted, and free resources are sparse. The internet provides teachers with endless possibilities to access copy-free materials that they can adapt, use according to their needs, and share with their community. These resources provide teachers with materials for their students' individual needs (Kimmons & Veletsianos, 2016) or other differentiated instruction needs (Blomgren, 2018).

The 2002 UNESCO Forum coined the term Open Educational Resources (OER) to describe teaching, learning, and research materials open for public use (Hewlett Foundation, 2013; UNESCO, 2002). The use of OER teaching materials poses several advantages for teachers. These specific forms of ER are mostly barrier-free because they are cost-free to search, use, and distribute. Through open source code, OER have limited technical barriers, and the lack of copyright and licensing restrictions results in fewer legal permission barriers (Hylén, 2006). Due to the advantages of OER, they are especially beneficial for educational institutions and structures in countries of the Global South when schools are not well-resourced, and free and online materials are a convenient way to quickly access teaching materials (e.g., Bateman, 2008; Kanwar et al., 2010).

ER, especially OER, are used worldwide in primary, secondary, and higher education (Hylén, 2006). For example, there are over 2,000 available university courses online, including content from top universities in China, France, Japan, the United States, and others (Hylén, 2006). Furthermore, there are numerous non-course OER available. For example, Rice University's OpenStax project hosts 2,800 learning objects, including textbooks, MERLOT offers over 15,000 resources, and ARIADNE offers web-links to networks and repositories. Although the available resources are diverse, teachers do not always seek and use OER for various reasons (Cox & Trotter, 2017). Teachers have reported lacking the following: OER awareness (e.g., Reed, 2012; Samzugi & Mwinyimbegu, 2013), access to relevant, high-quality OER (Clements & Pawlowski, 2012), personal interest or motivation to use OER (e.g., McGill et al., 2013; Pegler, 2012; Reed, 2012), and time for searching (Allen & Seaman, 2014). However, a recent study by Admiraal (2022) investigated the use and type of ER and the purposes of use of 675 K-12 teachers from 180 countries. The results show that 84.7% of K-12 teachers in the survey adapted ER and OER to fit their needs, and 38% created ER for study or teaching. The most commonly used ER by teachers in the study were videos (72.7%), images (65.4%), open textbooks (51.7%), lesson plans (46%), tutorials (40.1%), quizzes (41.3%), and learning tools (40.7%). Most participants indicated getting new ideas (80.8%) after searching for ER and using them to prepare to teach (71.2%).

The Role of Social Media in Educational Resource Acquisition

Teachers can access ER through different outlets. There are various ER repositories, including OER, and for-profit platforms, such as TeachersPayTeachers.com. Teachers often report time restrictions for searching content-related ER as a factor that prevents them from using more OER (Allen & Seaman, 2014). Studies have investigated the advantages of social media for sharing ER. For instance, Okada et al. (2012) and Mikroyannidis et al. (2011) found many benefits, like contact with a global audience, instant responses and editing, availability for web users without specialized skills, and low costs. Conole and Culver (2010) state that social media provides a dynamic and open environment for finding, sharing, and discussing learning, teaching ideas, and ER.

Furthermore, Atenas and Havemann (2014) identified social media as a tool for sharing OER. They pointed out that the advantage of social media is creating an environment where teachers can be part of a community and create a space for pedagogical innovation (Jacobi & van der Woert, 2012). The Paris OER Declaration recognizes the value of communities of practice (COP) sharing OER and collaborating (UNESCO, 2012). Torphy et al. (2020) investigated teachers' sharing and acquiring of ER on Pinterest (pinterest.com). This platform is used by teachers to share and save pictures (i.e., pins) by accounts that can be followed and appear on one's own curated pinboard (Carpenter et al., 2016). However, results from a study by Banzato (2012) show that, despite the potential advantages, acquiring OER via social media was still underdeveloped. The results of the investigation of 176 Italian teacher educators' perceptions and use of OER showed that even though the majority of participants (59.1%) used social networks for leisure time activities, only a small number (6.8%) used social media like Facebook, blogs, or wikis to find OER.

Sharing Educational Resources on X

X is a microblogging platform where users can communicate via limited short text with up to 280 Unicode characters (formerly known as *tweets*, now as *posts)*. After Twitter was purchased by Elon Musk in 2023 (Conger & Hirsch, 2022) and experienced a rebrand, the character limit expanded to 4,000 for paying users. These new features are not included in our data set. Posts can reference specific hashtags (#) and users by adding an @ before the users' names. Users can communicate through liking, commenting, and retweeting (i.e., sharing) other users' posts. Furthermore, they can follow other users' content and share it with their followers. These features provide opportunities for sharing resources, ideas, and feedback, and teachers' use of X has become of interest in the professional development literature. Several studies have reported X having properties of *affinity spaces* (e.g., Carpenter, 2015; Greenhalgh et al., 2020), characterized as online spaces where users of different prior knowledge and experience can create, share, and interact with content related to topics of shared interest. Identifying as part of a community helps teachers access information faster and builds trust in the quality of received materials (Fütterer et al., 2021). X seems to have proven especially useful to teachers seeking to network, exchange ideas, collaborate with colleagues for emotional support, and combat isolation (e.g., Carpenter & Krutka, 2014; Wesely, 2013). Importantly, X is a place to share and acquire materials and ER, as some studies suggested. For instance, Rosenberg et al. (2020) investigated 7,000 posts in the #NGSSchat community, which the researchers initiated as a venue for teachers to discuss the Next Generation Science Standards reform in the United States. The study's authors found that over half of conversations were transactional, meaning users showed affirmation of shared content, reframing previously shared content, and invitations to further discussions. Furthermore, a recent study by (Fütterer et al., 2021) that investigated the German X landscape during the COVID-19 pandemic showed that teachers used X to access relevant resources during emergency teaching, thus indicating the benefit of timely and easy access to personalized information and resources during disruptive events. Therefore, teachers can utilize X as a powerful resource for teaching materials and professional development.

Theory of Planned Behavior

Professional learning on social media is self-directed, and research on the effects of social media use on teachers and their influence on their classroom practice is difficult to associate with. However, teachers often post about their intentions to use ER that they found online; this intended behavior can already give insights into whether actions to implement them into classroom practice follow. Icek Ajzen and his colleagues developed the TPB in the late 1980s and 1990s. It is widely accepted and used to understand and predict human behavior in different disciplines, such as health, social psychology, and decision-making (Ajzen, 1991). The model has three basic assumptions. First, TPB assumes that human behavior is not random but follows a rational decision-making process. Secondly, it states that peoples' intentions are the immediate determinant of their behavior. Third, TBP names three factors influencing intention and behavior: attitudes towards the behavior, subjective norm, and perceived behavioral control. Attitudes toward behavior include positive and negative views of a particular behavior; beliefs regarding the outcomes of the behavior influence these views. Subjective norms represent the social pressure or influence from the social group to engage in or refrain from a behavior. Normative beliefs (i.e., beliefs about what important others think one should do) can strongly influence social media behaviors when active and influential users influence normative beliefs (Courneya & Friedenreich, 1997; Kim et al., 2016). Moreover, behavioral control reflects an individual perception of the difficulty level of performing a task. Notably, TPB states that the intention of a behavior is the most vital determinant and immediate precursor to behavior (e.g., Ajzen, 1991; Alwreikat, 2022; Doll & Ajzen, 1992; Truong, 2008). Several studies have examined TPB and X in the areas of economics and consumer behavior. For example, Chu et al. (2016) investigated how TPB can predict X users' brand-following behavior and purchase intention. The authors found that perceived behavior control directly influenced purchase intention.

User Attributes and Social Influence on X

Prior research suggests that certain user attributes on social media sites, like X, influence how posts are perceived by the community. For example, Hutto et al. (2013) investigated factors that contributed to the follower growth of X users in a longitudinal study, thus marking an increase in their social influence. The authors found that the content of posts contributed to follower growth, with informative content and well-written posts attracting more users. Furthermore, profiles with complete user descriptions and personal information seem more attractive to users. Other communication techniques, like sending direct messages over broadcast messages, increase follower growth. This shows that some users can acquire more influence on X than other users. Rehm and Notten (2016) investigated posts from #EdchatDE (22nd of May 2014-21st of May 2015). They found that 78% of user accounts with the most followers belonged to large, international cooperations and news portals, such as YouTube, the New York Times, Google, and Edutopia. The authors argued that specific individuals in the #EdchatDE community could attain central positions within the conversations and that sub-clusters of users gravitate around these central users over time.

In the medical field, Desai et al. (2014) investigated factors contributing to social media influence in the #APDIM13 (i.e., *2013 Association of Program Directors in Internal Medicine meeting*). The authors defined influence as the number and directionality of mentions from users within the community. They classified the users into four types: faculty, organizations, others/uncategorizable, and trainees/residency programs. They found that faculty members had the most significant influence, not necessarily because they were viewed as experts by the other users but because they posted the most. This finding indicates that within this community, the frequency of posts was more influential than experience or perceived trust in the users.

Besides social influence, some factors can contribute to how credible users perceive posts and resources. For example, having too many or too few followers can result in a lower judgment of expertise and trustworthiness (Westerman et al., 2012). The number of followers can thus be an essential feature on which trustworthiness is decided. A study on celebrity endorsers on X found that celebrity endorsers with many followers were viewed as more trustworthy than celebrity endorsers with fewer followers (Jin & Phua, 2014). Also, consumers indicated significantly more intentions of starting an online relationship with the endorser with higher follower counts.

In summary, studies showed that certain user features contribute to their popularity, influence within the community, and perception of shared content. Little research has been done on the most relevant user attributes when explaining teachers' X use.

Perceived Use and Quality of Resources for Teaching

The quality of ER has been subject to many studies and debates and is the most critical concern for resources. As more resources are freely accessible, and everyone can modify and redistribute them, no external committee ensures high-quality standards. Teachers need to validate the quality of resources. Quality assessment can be executed differently (Clements & Pawlowski, 2012). For example, peer reviewing is an approach adopted by many OER repositories like ARIADNE or MERLOT that review through rankings, commenting, social tags, or peer production (Auvinen & Oy, 2009). Furthermore, teachers assess the quality of resources based on recommender systems within their communities (e.g., Burke, 2002; Manouselis & Sampson, 2004). Another quality assessment is through trust and trust-based systems. According to Clements & Pawlowski (2012), the quality of resources depends on the authors, typically individuals or organizations. The authors investigated trust as a critical instrument for facilitating the re-use process for teachers, especially in the selection of resources. The survey results with 136 European teachers of information and communications technology or mathematics showed that 82% found resources based on recommendations from colleagues and 71% based on recommendations from personal friends. In contrast, only 51% searched for well-ranked resources or resources from organizations with good reputations. Even though searching by browsing topics and subjects is the most prominent search method (89%), the results showed that trust and recommendations play an essential role in the teachers' search process. Furthermore, 82% of participants viewed recommendations as the quality criteria they were most familiar with, indicating a strong connection between trust and perceived quality.

Many studies suggest that teachers perceive the quality of online resources as satisfactory, comparable, or even better than traditional textbooks (e.g., Carpenter & Shelton, 2023; Hilton, 2016; Kimmons, 2015). Importantly, studies have shown that learning outcomes in classrooms where ER and OER serve as teaching materials are comparable to classrooms where traditional teaching materials are utilized (Lin & Tang, 2017; Tang & Bao, 2020).

Research Questions

This study is the first to provide quantitative evidence outside of questionnaire data of teachers using X to share and acquire ER. Therefore, this study can advance the theoretical underpinnings of X as an example of a social media platform to share and acquire ER. Moreover, this study investigates factors, such as users' higher popularity, influence, and perceived trustworthiness, that contribute to how ER are shared and perceived. This study suggests practical implications for educational stakeholders and PD providers to promote participation in online communities for ideas and inspiration on improving teaching practices. Furthermore, the paper provides a methodological framework for investigating the use of ER, which can be applied to X datasets derived from different countries and teacher communities. In this article, we want to answer the following research questions (RQ):

(RQ1) Which types of ER are shared in educational X communities?

(RQ2) How are ER shared and perceived in educational X communities?

(RQ3) How are ER reportedly used in instructional contexts?

(RQ4) How are user characteristics associated with ER interaction patterns?

Method

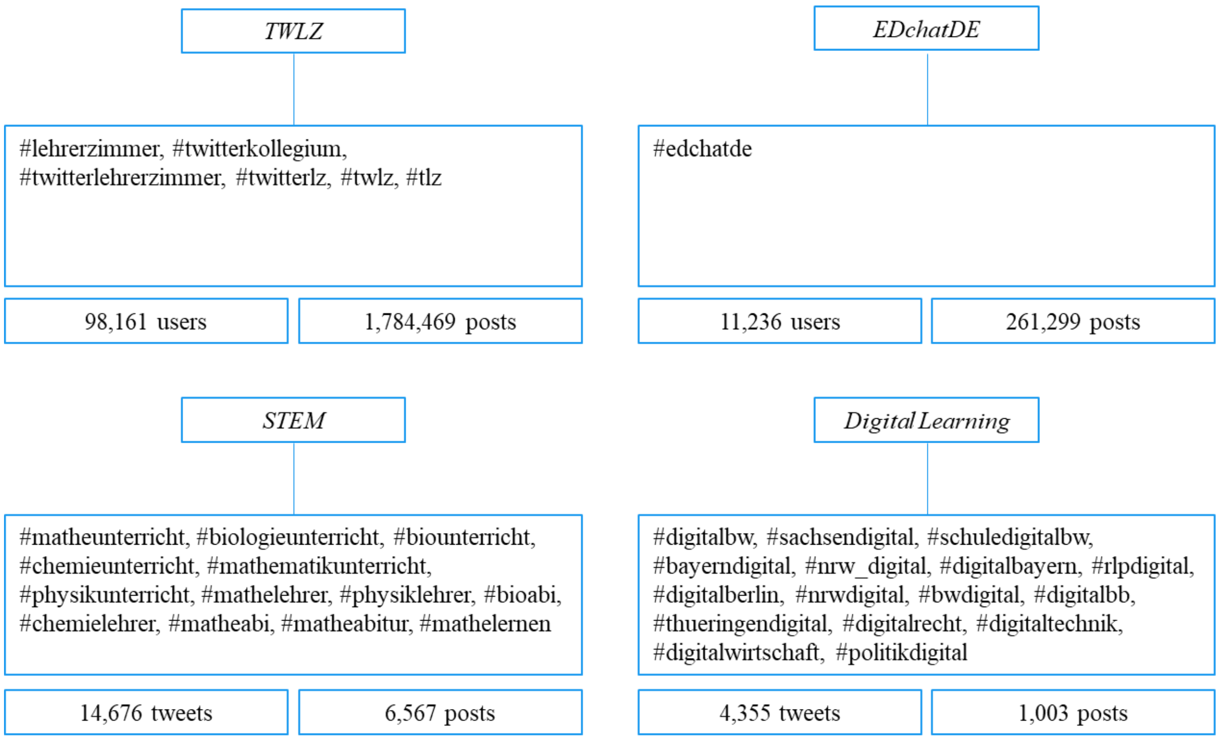
Sample Description

Data were downloaded through the X Academic API 2.1 with custom *R* and Python scripts between April 8th and April 25th, 2022 (Fischer et al., 2023). The data download and pre-cleaning scripts are under the project's GitHub repository.

This project examines four types of hashtag communities, each with a different focus. The four community types were obtained by combining related individual hashtag communities within (a) EdchatDE, (b) STEM, (c) Digital Learning, and (d) the *Twitterlehrerzimmer* (TWLZ), Germany's largest teacher X community (Fütterer et al., 2021; Figure 13). At the time of data collection, the TWLZ community included 1,784,469 posts from 98,161 users. It consisted of six hashtags that share an abbreviation of the word *Twitterlehrerzimmer* (German for *Twitter teachers' lounge*). The chat-based community EdchatDE had 261,299 posts from 11,236 users. It only included the hashtag #EdchatDE, where teachers and other educators have met regularly to discuss a topic initiated by one of the moderators. The STEM community consisted of 13 individual hashtag communities related to STEM subjects, which included 14,676 posts from 6,567 users. Finally, the Digital Learning community consisted of 16 individual hashtag communities that discussed topics around the implementation of digital tools into classrooms and teaching and included 4,355 posts from 1,003 users. See Figure 13 for an overview of included hashtags within communities.

Figure 13

Description of Community Types



Measures

First of all, we defined ER as links or other media that are being shared. Notably, more than one resource can be shared within a post.

For each community type, we created variables that can be categorized into two different categories: *post-level variables* and *user-level variables*.

Post-level variables included the post text, a dichotomous variable indicating whether the post contains links, a dichotomous variable whether the post contains media, and the type of media included in the post (photos, videos, GIF). Additionally, we investigated the number of GIFs that were shared, which also comprised a small percentage (EdchatDE: 1.26%; STEM: 7.66%; Digital Learning: 17.64%, and TWLZ: 14.43%). However, we believe that GIFs are a form of expression rather than resources and, therefore, neglectable (Sasamoto, 2023). We also included the post sentiment (dichotomous with -1 indicating negative sentiment and 0 indicating neutral/positive sentiment) and continuous variables indicating the number of likes, reposts, and replies. Furthermore, dichotomous variables indicate whether a post is a sparking post (i.e., the initial post) of a conversation (all replies to a sparking post).

User-level variables included a user classification (teacher/non-teacher). Teachers were identified based on 1000 randomly sampled profiles (e.g., Pennacchiotti & Popescu, 2011), on which training data for an automated logistic regression classifier using textual features of user bios and posts were generated. Moreover, two human coders evaluated 250 users' X bio and up to 50 randomly sampled posts and assigned them to either *teacher* or *non-teacher*. Non-teachers can be educational institutions, counselors, political institutions, parents, principals, academic staff, researchers, or bots. One hundred eighty-seven users identified as bots were excluded from the dataset. Furthermore, we included the eigenvector-centrality of a user, which is a social network measure, indicating how influential the user is within the network, using the in-and-out-degree nodes (Bonacich, 2007).

In the TWLZ community, 10.3% of posts were from teachers. In the EdchatDE community, 42.6% of the total posts were by teachers. In the STEM community, 15.7% of posts were by teachers. Moreover, in the Digital Learning community, 50% of posts were by teachers. Further user-level variables included continuous variables describing the number of followers, number of total posts, number of average posts per day, number of replies, number of reposts, number of quotes (quoted reposts), and user lifespan.

To investigate text patterns and topics in more detail, we used the Linguistic Inquiry and Word Count software (LIWC; Boyd et al., 2017), a natural language processing approach that has found widespread use in investigating what users share online (Boyd, 2017; Tausczik & Pennebaker, 2010). LIWC contains dictionaries in several languages and counts the percentages of words within a text that fall into prespecified categories (Stevens et al., 2021). The categories include various psychological processes like drive, cognition, memory, and affect, as well as social processes like prosocial behavior, politeness, and interpersonal conflict. For our analysis, we examined the LIWC categories positive tone, negative tone, insight (words like knowing, thinking, feeling), and acquire (words like get, got, take, getting). LIWC calculates the percentage of words attributed to the categories relative to all words in the post. For example, if 3 out of 35 (1.05%) words in a post can be attributed to the category *positive tone*, the post would get a score of 1.05. We then calculated the mean scores for all categories of generative posts containing materials and generative posts not containing materials and their replies.

Analytical Methods

To answer RQ1, we defined ER as links or media referenced in the posts. We then calculated the percentage of posts (including generative posts, reposts, replies, and quotes) that contain resources within the four community types. We did this for posts from teachers and non-teachers.

To answer RQ2, we calculated the sentiment for each post. We compared the sentiment score of posts that contained ER with posts that did not contain ER within each community type and for teachers and non-teachers. The sentiment of posts was calculated based on the German sentiment dictionary *SentimentWortschatz* (Version 2.0; Remus et al., 2010, May). We calculated the sentiment ratio of the number of posts with a negative sentiment divided by posts with a positive/neutral sentiment (Wang & Fikis, 2019). Furthermore, we use the LIWC variables *positive tone* and *negative tone* to investigate the mean percentages of words associated with either positive or negative sentiment.

For RQ3, we used a keyword analysis to examine whether classroom materials are implemented for each community type. To do this, we extracted all conversations with a generative post where ER were shared. Then, we extracted all the replies to the generative post. Next, for each community type, two independent coders read 500 random posts of the reply chains, coding each post that indicated that the shared resources were implemented or intended to be implemented in the classroom. We subtracted the most frequent action words from these posts and created a wordlist, which we ran over the remaining posts of our datasets. We did this on the posts of all community types and separated them into teachers' and non-teachers' posts.

To answer RQ4, we used logistic regression to investigate the association between a) posts that contain ER (all kinds of posts: generative posts, replies, reposts, and quoted posts), b) generative posts with ER indicating usage of shared resources in the reply chain, c) generative posts without ER indicating usage of shared resources in the reply chain and their perceived sentiment and indication of use. The independent variable is a binomial variable stating 0 = post does not contain educational resources, 1 = post contains ER, 0 = replies to the generative post with ER do not indicate usage, and 1 = replies to the generative tweet with ER indicate usage.

Results

Media Types of Educational Resources in Educational Communities

In the EdchatDE community, 32.7% of posts (37.1% posted by teachers) contained one or more resources. In the TWLZ community, 49.6% of posts included resources (51.4% posted by teachers). In the STEM community, 51.2% of posts included resources (25% posted by teachers). Lastly, 56.8% of the Digital Learning community posts contained resources (51.5% posted by teachers).

From posts containing ER, almost all of them were links (EdchatDE: 98.8%; STEM: 96.6%; Digital Learning: 92.8%; and TWLZ: 92.2%). Photos were the most shared media type (EdchatDE: 98.3%; STEM: 89.3%; Digital Learning: 79.8%; TWLZ: 67.6%). Videos comprised only a minority of resources in all community types but were shared the most in the

TWLZ community (EdchatDE: 0.46%; STEM: 3.05%; Digital Learning: 2.58%, and TWLZ: 17.92%).

When comparing the sharing patterns between users defined as teachers and users defined as non-teachers, the result suggests that sharing patterns of media differ between teachers and non-teachers. For example, non-teachers share videos in all community types more than teachers.

How Are Educational Resources Shared and Perceived in Educational Communities?

When investigating sharing behavior over the years in the four communities, it is evident that the sharing of resources has increased substantially in two, while it has dropped off in EdchatDE and the Digital Learning community. Figure 14 shows the time series of shared materials in a log scale to make the relative changes more comprehensible. Notably, TWLZ has significantly increased user activity and shared resources from 2018 on, while sharing activity in EdchatDE peaked between 2015 and 2018 and then declined. Resource sharing in the Digital Learning community hashtags started in 2017, peaked in 2018, and then declined gradually.

Figure 14

Log-Scaled Number of Shared Educational Resources in all Four Communities

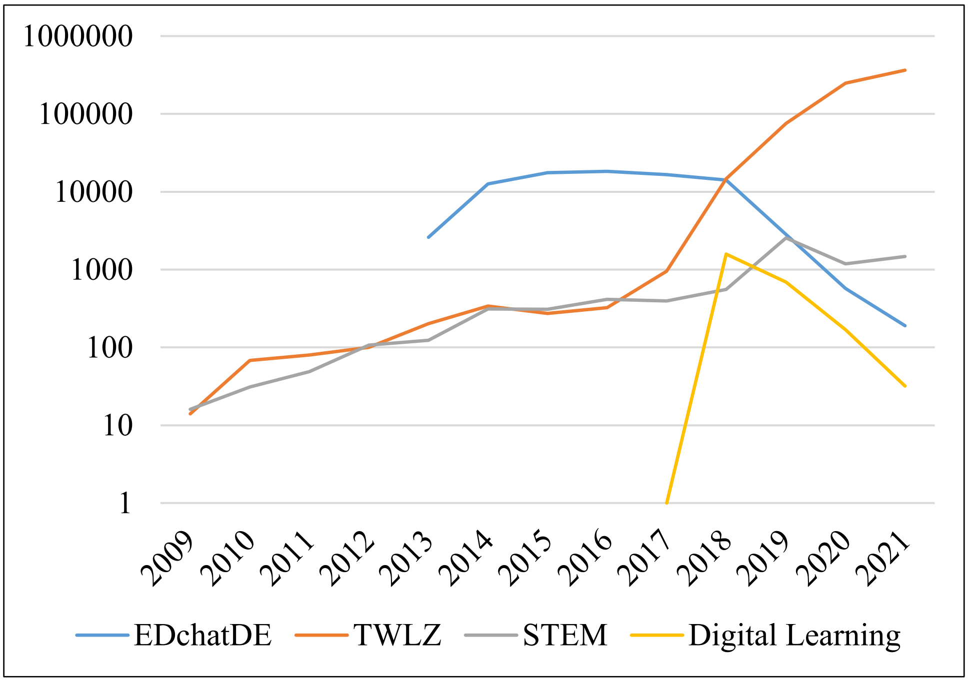
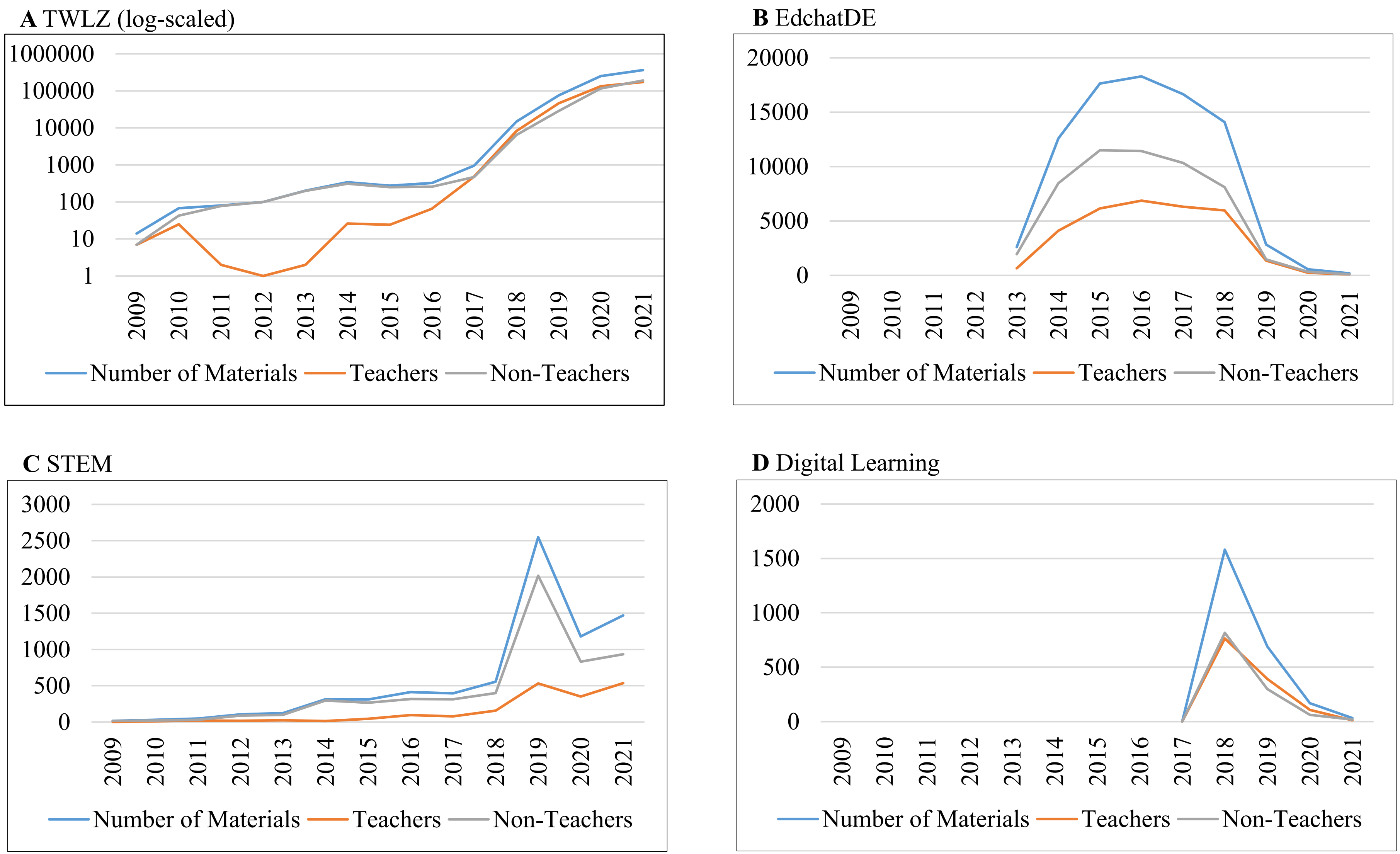


Figure 15 shows the sharing patterns of ER amongst users classified as teachers and non-teachers for comparison. For TWLZ (Figure 15A), resource sharing started to rise noticeably around 2017, with the activity only increasing during the COVID-19 pandemic (2019-2021). Initially, more teachers shared ER than non-teachers until the year 2021. Between 2010 and 2013, there was a steep decline in materials shared by teachers, while the number of shared ER was constant for non-teachers. For EdchatDE (Figure 15B), more non-teachers shared resources than teachers. Notably, resources were shared from 2013, when the EdchatDE was initialized, until around 2019, when the weekly chats stopped. However, some materials are still being shared, suggesting that the community did not die out entirely. Sharing ER in the STEM community (Figure 15C) started in 2009, with more non-teachers sharing ER than teachers. In 2019, the sharing of ER peaked, with 2548 materials being shared. More materials were shared by users classified as non-teachers than teachers. In 2020, shared materials declined but showed an increasing pattern again in 2021. Finally, the Digital Learning (Figure 15D) community only emerged in 2017, and the sharing of materials peaked in 2018, with 1,580 materials being shared. In this community, users classified as teachers shared approximately a similar number of ERs as users classified as non-teachers.

Figure 15

Sharing Patterns of Educational Resources in Online Communities. Note the different y-axis labels between the figures.



For the sentiment analysis, we found that posts in the TWLZ community had a general sentiment score of 0.29 (ratio of negative to neutral/positive posts). In contrast, in the STEM community, the sentiment was slightly more negative, with a ratio of 0.3. In the Digital Learning community, the sentiment was more positive, with a ratio of 0.19, and the sentiment of posts in the EdchatDE community was the most positive, with a sentiment ratio of 0.15. The text analysis with LIWC revealed that in the TWLZ community, teachers used a mean of 4.8% positive words per post (4.14% for non-teachers) and 1.13% negative words per post (1.29 % for non-teachers). In EdchatDE, teachers used a mean of 4.49% positive words and 1.02% negative words, whereas non-teachers used a mean of 4.02 % positive words in posts and 0.84% negative words. In the STEM community, 4.66% of words in posts were positive on average for teachers, 3.07% were negative for non-teachers, 1.03% were negative for teachers, and 2.38% were negative for non-teachers. In the Digital Learning community, 4.56% of words in posts were positive for teachers (4.40% for non-teachers), and 0.77% were negative (0.77% for non-teachers).

We found that replies to posts with materials had similar sentiment scores in all communities. In the TWLZ community, posts had mean sentiment scores of 0.27 (0.27 for replies to posts without materials), a sentiment ratio of 0.17 for the EdchatDE community (0.17 for replies to posts without materials), a sentiment ratio of 0.3 for replies to posts with materials in the STEM community (0.31 for replies to posts without materials), and a sentiment ratio of 0.21 in the Digital Learning community (0.22 for replies to posts without materials).

Next, we examined the differences in sentiment ratios between teachers and non-teachers for replies to posts with materials within the communities. For teacher replies, the sentiment ratio was 0.25 in the TWLZ community, while it was 0.29 for non-teachers, indicating slightly more negative sentiment for non-teachers. In the EdchatDE community, teachers' replies had a sentiment of 0.18, and non-teachers had a sentiment of 0.16, indicating a slightly more negative sentiment from teachers. In the STEM community, teachers' replies had a sentiment of 0.21; for non-teachers, it was at 0.35, showing a more negative sentiment of non-teachers. Lastly, teachers in the Digital Learning community had a sentiment ratio of 0.2, and non-teachers had a sentiment of 0.22.

Usage of Educational Resources in Instructional Contexts

The coding process revealed 10 words that indicate usage of ER: "ausprobieren", "nutzen", "einsetzen", "genutzt", "nutze", "probiert", "anwenden", "verwenden", "anschauen", "anwendung". These ten words were our initial keywords in step 1. For step 2, we looked for similar words to those we found through coding with an online thesaurus, and we could identify three more words (“benutzen”, “heranziehen”, “austesten”). The keyword search with this keyword string yielded a small percentage in all community types. For the TWLZ community, 2.89% of posts showed at least one of the words in the wordlist, with 3.34% for teachers and 2.45% for non-teachers. For the EdchatDE community, 2.21% of posts contained a keyword, with 2.79% of teacher posts and 1.73% of non-teacher posts. In the Digital Learning community, 3.14% of posts contained at least one keyword, with 2.47% of teacher posts and 3.78% of non-teacher posts.

In the STEM community, 2.43% of posts contained a keyword, with 4.97% of posts from teachers and only 1.44% from non-teachers. The chi-square test showed that, as would logically be expected, in the EdChatDE community and the TWLZ community, significantly more users identified as teachers than non-teachers showed signs of implementing ER in their classrooms.

Table 7

Chi-Square Test Results Between Teacher and Non-Teacher

Community Type	Counts		Chi-square test results
	Teachers	Non-teacher	
EdchatDE	241	179	$\chi^2 = 9.15$, df = 1, $p = .002$
STEM	39	29	$\chi^2 = 1.47$, df = 1, $p = .225$
TWLZ	7,034	4,654	$\chi^2 = 484.63$, df = 1, $p < .001$
Digital Learning	17	27	$\chi^2 = 2.27$, df = 1, $p = .13$

The Association Between User Characteristics and Educational Resources Usage

For this research question, we investigated how user characteristics are associated with sharing, perceiving, and indication of usage using logistic linear regression. The logistic regression analyses (Table 8) showed that for EdChatDE, the user being a teacher ($OR = 0.85$, $p < .001$) decreases the odds of a tweet with ER having a positive sentiment. For STEM, the eigenvector centrality ($OR = 2.64$, $p =.011$) increases the odds of a post having a positive sentiment. For TWLZ, the eigenvector centrality ($OR = 6.27$, $p < .001$) and the user being a teacher ($OR = 1.17$, $p < .001$) increased the odds of sharing a post with ER with positive sentiment. This suggests that teachers who are highly connected within their network perceive ER more positively than ER from other users.

Table 8

Results of the Logistic Regression with Odds Ratio of User Characteristics and Sentiment

Variable	*n*	β	*SE* β	Wald's χ^2	*p*	Odds ratio (e^{β})
EdchatDE						
Intercept	74,374	2.307	0.026	89.890	<.001	
User follower count		<0.001	<0.001	**-1.975**	**0.048**	**0.999**
User total tweet count		<0.001	<0.001	0.215	0.829	1.000
Eigenvector-centrality		**0.254**	**0.039**	**6.464**	**<.001**	**1.288**
User is teacher		**-0.155**	**0.029**	**-5.420**	**<.001**	**0.857**
STEM						
Intercept	3,545	1.425	0.055	26.124	<.001	
User follower count		<0.001	<0.001	-1.401	0.161	0.999
User total tweet count		<-0.001	<0.001	-8.511	<.001	0.999
Eigenvector-centrality		**0.972**	**0.380**	**2.557**	**0.011**	**2.643**
User is teacher		0.121	0.096	1.258	0.208	1.129
Digital Learning						
Intercept	1,576	1.610	0.135	11.962	<.001	
User follower count		<-0.001	<0.001	-0.976	0.329	0.999
User total tweet count		<-0.001	<0.001	0.910	0.363	1.000
Eigenvector-centrality		-0.004	0.280	-0.013	0.989	0.996
User is teacher		-0.076	0.141	-0.539	0.590	0.927
TWLZ						
Intercept	626,988	1.026	0.005	224.212	<.001	
User follower count		<0.001	<0.001	**22.643**	**<.001**	**1.000**
User total tweet count		<-0.001	<0.001	**-39.242**	**<.001**	**0.999**
Eigenvector-centrality		**1.836**	**0.045**	**41.260**	**<.001**	**6.269**
User is teacher		**0.156**	**0.006**	**26.324**	**<.001**	**1.169**

Furthermore, logistic regression analyses (Table 9) showed that for EdChatDE, the user being a teacher (*OR* = 1.42, p < .001) increases the odds of ER being used. For STEM, too, the user being a teacher (*OR* = 8.42, p < .001) increased the odds. In the Digital Learning community, only the eigen-centrality (*OR* = 9.06, p < .001) increased the odds of using the ER in classroom practice. For TWLZ, the eigenvector centrality (*OR* = 63.24, p < .001) and whether the user is a teacher (*OR* = 1.21, p < .001) increase the odds of shared ER being used in teaching practice. The results suggest that ER shared by highly influential teachers (as indicated by higher eigenvector-centrality) are more likely to be implemented into classroom practice.

Table 9

Results of the Logistic Regression Analysis with Odds Ratio of User Characteristics and Indication of Use

Variable	*n*	β	*SE* β	Wald's χ^2	*p*	Odds ratio (e^{β})
EdchatDE						
Intercept	155,843	-6.050	0.120	-50.240	<.001	
User follower count		<0.001	<0.001	0.472	0.637	1.000
User total tweet count		<-0.001	<-0.001	**-3.042**	**0.002**	**0.999**
Eigenvector-centrality		-0.349	0.224	-1.563	0.118	0.705
User is teacher		**0.338**	**0.125**	**2.696**	**0.007**	**1.402**
STEM						
Intercept	3,807	-5.597	0.332	-16.880	<.001	
User follower count		<0.001	<0.001	**3.928**	**<.001**	**1.000**
User total tweet count		<-0.001	<0.001	-0.477	0.634	0.999
Eigenvector-centrality		1.500	1.032	1.454	0.146	4.483
User is teacher		**2.131**	**0.371**	**5.737**	**<.001**	**8.421**
Digital Learning						
Intercept	1,443	-4.465	0.418	-10.679	<.001	
User follower count		<0.001	<0.001	1.070	0.285	1.000
User total tweet count		<-0.001	<0.001	-0.701	0.483	0.999
Eigenvector-centrality		<0.001	**0.618**	**3.565**	<.001	**9.063**
User is teacher		-0.352	0.454	-0.775	0.438	0.703
TWLZ						
Intercept	692,552	-4.700	0.023	-205.639	<.001	
User follower count		<0.001	<0.001	**9.263**	**<.001**	**1.000**
User total tweet count		<-0.001	<0.001	**-20.723**	**<.001**	**0.999**
Eigenvector-centrality		**4.147**	**0.073**	**57.046**	**<.001**	**63.236**
User is teacher		**0.188**	**0.026**	**7.150**	**<.001**	**1.207**

Discussion

This study provides an innovative look into the sharing patterns of ER on social media platforms. It gives a new insight into if ER are implemented into classroom practice and, therefore, of practical use for teachers. By investigating four important community types within the German X-Sphere, we comprehensively overview the most relevant venues for the informal sharing of ER. Using big data analysis, our paper aims to advance methods in educational research, which traditionally rely on questionnaires and teacher's self-reported data. Furthermore, this study draws direct links to the Theory of Planned Behavior by investigating how teacher-level variables (sharing behavior, sentiment, popularity) affect their classroom behavior (intent to use).

Interaction Patterns of Educational Resource

Our study indicates that ER are being shared across all X community types. The highest total number of resources was shared in the Digital Learning community and the lowest in the EdChatDE. The lower percentage of media/links associated with EdchatDE might indicate that this community functions more as a place of social connection and emotional support within a guided setting, moderated by different topics every week, rather than a place where miscellaneous ER are being shared (Rehm & Notten, 2016). In contrast, the STEM and Digital Learning communities are more limited in their topics of interest and more unguided in their format, which might encourage teachers to use them to share and acquire materials at their own pace and needs (Fischer et al., 2019). Another interesting finding is that ER shared by non-teacher users constitute the majority in the EdchatDE and STEM community and only around half of users in the TWLZ and Digital Learning community. This can have different explanations. First, the user classifier employed in this paper was based mainly on the user bio and randomly sampled posts. Not all users indicated a bio, so some teachers might not have been detected. Furthermore, as communities are based on hashtags, everyone interested in the topic can participate, as there is no external regulation of who belongs within an X community. Communities are formed organically, based on shared interests, domain, and practice (Fischer et al., 2023, 29. April). In line with other research (Admiraal, 2022), links and images are among communities' most shared ER. However, the popularity of other media types varies between the communities. GIFs can indicate that emotional and anecdotal information (Shmueli et al., 2021) is being shared alongside weighty materials, improving the overall sentiment of the communities. Overall, our results suggest that different communities show different sharing patterns and have different purposes for their users. Another observation is that activity patterns within and across communities varied. (Borchers et al., 2023) found that 65.98% of users in the

EdChatDE community switched to the TWLZ community over their lifespan, showcasing that switching between communities is a common practice and important so that users can get the information they need at a particular moment.

The post sentiment in each community is generally more positive than negative, suggesting supportive community structures (Rosenberg et al., 2021). Sentiment for posts by teachers was generally more positive than that of non-teachers, suggesting they might feel a stronger sense of belonging to the community (Fischer et al., 2023, 29. April). The sentiment of replies for posts containing ER did not differ from replies of posts that did not, indicating that users did not have a more positive sentiment in their replies. This might mean that although ER might be perceived as valuable, users do not express more positive sentiments overall. However, in some communities, like the TWLZ or the STEM community, teacher replies to posts with materials were more positive than non-teachers, indicating that the users who found shared ER helpful expressed it more clearly in the replies.

Usage Patterns of Educational Resources

The usage patterns showed a small percentage of posts in each community that exhibited signs of action words indicating German usage. According to the TPB, the intention of an action is the strongest predictor of acting (Ajzen, 1991). Therefore, we suggest that ER that show the intention of usage will likely be implemented in classroom practice. We can argue that with the keywords we chose, we found action words indicating strong intentions like “nutzen” (to use), “implementieren” (to implement), and others. The small percentage of posts indicating usage might suggest that social media can be a place for sharing valuable resources and materials.

User Characteristics Associated with Usage of Educational Resources

We found two user characteristics to be the most influential: eigenvector-centrality and whether the user is classified as a teacher. Resources that were shared by teachers with high eigenvector-centrality, meaning that they were very influential, had posts with more positive sentiment, and the shared resources were more likely to be implemented based on eigenvector-centrality. These findings align with several other research projects; for example, Bliss et al. (2012) found that users who are more connected within their network share happier posts. Rehm and Notten (2016) found that specific individuals could be more central in the EdChatDE community and serve as influential opinion-makers. Other user characteristics found by literature, like the number of posts (Desai et al., 2014; Jin & Phua, 2014) or the number of followers (Westerman et al., 2012), did not significantly influence the sentiment in our study. As other research suggests, eigenvector centrality within the community has the most substantial influence on the users within the community as they are often deemed as more trustworthy, their posts perceived as having a higher quality and being shared more often within the community (Desai, 2014; Rehm & Notten, 2016).

Limitations and Future Work

The nature of the data set induces several limitations for our work and results. First, due to privacy restrictions, we did not have access to the content of shared ER. Therefore, no causal claim about the quality of used resources can be made. Future research should extend the first steps we took in identifying and quantifying the sharing and usage of ER to investigate and consider the quality of these resources. Furthermore, future research could extend our data by including self-reported questionnaires for teachers who asked about sharing and usage patterns of ER found on X or other social media. Together with behavioral data/extensive data analysis and questionnaire, we could build a more comprehensive picture of the implementation into classroom practice and the perceived quality of online ER.

Another limitation is the representativeness of our data regarding the scope and the number of teachers we were able to classify, as well as the period of posts we downloaded. For the former, we had a comprehensive overview of different disciplines and topics of interest, like the STEM and the Digital Learning community, and were able to gain insight into the two largest mischievous communities. However, as not all teachers participate in online communities, we can only make conclusions about the active and engaging users within these communities. Unfortunately, it is impossible to know the exact number of teachers that frequently use these communities as places of inspiration without engaging, liking, following, or posting and reposting. Therefore, our conclusions are only limited to active users within these communities.

Conclusion

This study offers a unique insight into how teachers share, perceive, and use ER on social media platforms like X. Furthermore, it gives evidence of the importance of informal online professional development and collaboration between teachers. Instead of relying on self-reported questionnaire data, this study uses big data analysis of behavioral social media data from a huge dataset of the past 18 years. Drawing on the theory of planned behavior, the results of the text analysis of posts suggest that some teachers show indications of implementing the ER into their classroom practice.

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6

General Discussion and Conclusion

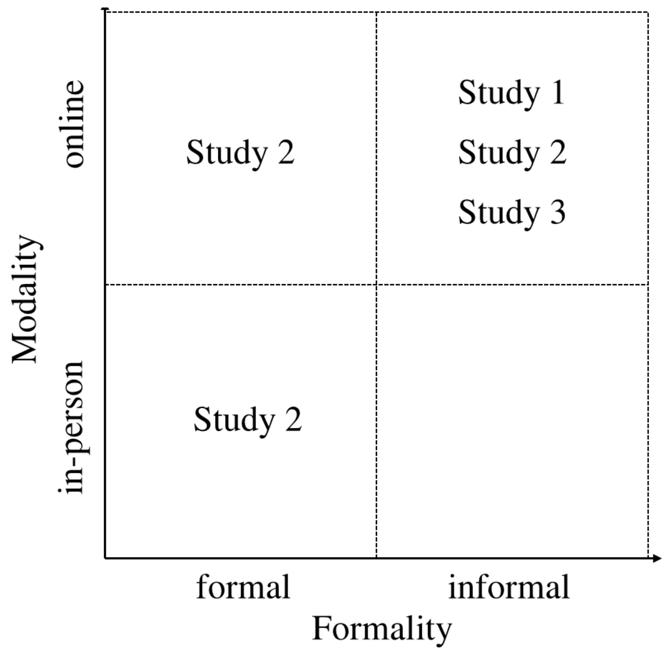
6 General Discussion and Conclusion

When teachers participate in effective PD, they experience a change in their knowledge skills, attitudes, and beliefs, which then influences their classroom practice. From this improved classroom practice, their students show higher content knowledge and achievements (Desimone, 2009). Traditionally, formal in-person PD has been viewed as the standard of PD formats, mainly consisting of in-person workshops where teacher trainers lecture about a specific topic, such as the content of educational reforms. In the last few years, due to the rise of technology and disruptive events like the COVID-19 pandemic, more innovative and informal forms of PD have emerged, such as online PD (OPD; for example, on websites, online courses, or social media). However, there is a lack of theoretical frameworks and empirical research on the effectiveness of OPD, its impact on classroom and student outcomes, and the potential of informal OPD participation for teachers' classroom practice.

My dissertation aims to close this gap in the literature by answering two research questions in this dissertation. First, I examined the existing literature on the effectiveness of OPD participation at the teacher, classroom, and student levels. Second, in two empirical studies, I answered how informal OPD participation in online communities influenced teachers' classroom practices. By classifying the studies into the model of the two teacher PD dimensions (Figure 16), the dissertation studies each have an individual focus, which gives a comprehensive insight into different aspects of OPD effectiveness.

Figure 16

The Dimension of Teacher Professional Development



This dissertation first sheds light on the effectiveness of OPD participation in a meta-analysis (Study 1). My results showed that OPD participation has a medium effect size on teacher-level outcomes and classroom practice and a small effect size on the student level, suggesting that OPD participation of teachers ultimately benefits their students. Interestingly, Desimone's (2009) proposed core features, as noted in her model of PD, did not significantly moderate the effect sizes in OPD. This might suggest that different features, like collaborative learning and accessibility of online materials, are more important for OPD than for in-person PD. Secondly, I found that informal OPD in online communities was promising for teachers in the context of educational reforms (Study 2). The results showed that participation in online communities like the APTC before implementing the AP redesign helped teachers implement more laboratory investigations and inquiry activities. Finally, I showed how informal OPD can be operationalized through sharing and acquiring educational resources in online communities on X (Study 3). The data from the teachers suggests that materials are intensively shared in online communities and that teachers intend to implement materials they found online into their classroom practice.

The three empirical studies suggest that investigating teachers' participation in OPD yielded positive results about its effectiveness and that participation in informal OPD exhibited promising results for influencing their classroom practice.

In the following section, I discuss the results of the three empirical studies (Chapter 6.1), the strengths and limitations of the results (Chapter 6.2), general implications for practice and research, and future directions (Chapter 6.3) before concluding this dissertation (Chapter 6.4).

6.1 Discussion of the Results

6.1.1 The Effectiveness of Online Professional Development

Teachers' participation in PD is necessary to ensure educational effectiveness. As outlined in Chapter 1.1, teachers' PD has a long history and was especially important during reforms or when usual classroom practice was disrupted. However, the quality of early PD programs could not be ensured, partly due to a lack of empirical evidence about what features make them effective. Since most countries mandate a certain amount of hours for PD participation, millions of teachers worldwide participate in PD, making it crucial for PD to adhere to quality standards. Early conceptual frameworks have been used to categorize how PD participation affects teachers (Chapter 1.2). Based on the theory of teacher change (Section 1.2.1), three levels of outcomes were established: the teacher, the classroom, and the student level. Desimone's (2009) conceptual framework of effective PD summarized and reviewed empirical research investigating five core features of effective in-person PD participation. These five core features have been proven by ample research to elevate outcomes of teachers' PD participation for in-person PD, including several systematic reviews and meta-analyses (e.g., Desimone et al., 2013; Kennedy, 2016; Kraft et al., 2018; Kyndt et al., 2016; Lindvall & Ryve, 2019; Postholm, 2012; Sims et al., 2021; Yoon et al., 2007).

However, as I have established in Chapter 1.3, teacher PD can be described along two dimensions, formality and modality, and research on the modality of online PD and informal PD is still understudied. Researching OPD is crucial, as PD has shifted increasingly into online formats due to many advantages over traditional in-person PD. Even though many individual studies examined the effectiveness of OPD participation on the teacher (Section 1.4.1), the classroom (Section 1.4.2), or the student level (Section 1.4.3), comprehensive data in the form of a meta-analysis, considering all forms of OPD, is missing.

Therefore, Study 1 investigated the effectiveness of teachers' OPD participation on three levels of outcome, the teacher, classroom practice, and student level, and aggregated empirical evidence from studies conducted in the last 15 years in a meta-analysis.

The results showed that OPD participation had the highest impact on outcomes at the teacher level, with an effect size of Hedges' $g = 0.66$. Outcomes on the teacher level included teacher knowledge and skills, teachers' attitudes and beliefs across all subjects, and school grades. Most OPD programs specifically target outcomes on the teacher level by focusing the content on these outcomes, like mathematic content knowledge (Avineri, 2016) or English language arts knowledge (de Kramer et al., 2012). Most of the studies included in the meta-analysis showed a positive effect size, with over 90 outcomes even having an effect size over

Hedges' $g = 1.0$. These studies with high effect sizes targeted teachers' knowledge of algebra (Hott et al., 2019), teachers' technological content knowledge (Machado & Laverick, 2015), teachers' pedagogical content knowledge (Dash et al., 2012), and teachers' knowledge of working with children with autism (Rakap et al., 2015). Sixteen effect sizes in the sample showed a negative effect size after OPD participation for teachers' pedagogical beliefs (Carey et al., 2008) or inclusive assessment practices (Derri et al., 2012). However, these results indicate that, in most cases, participation in OPD helped teachers gain a better understanding and knowledge of the targeted outcomes.

The effectiveness of OPD participation might be influenced by other factors, like the structure, OPD features, and the type of assessment, indicating that participation and the high quality of OPD are crucial for its effectiveness. Interestingly, some effect size directions vary within a study, with some outcomes having positive effect sizes, while the same OPD program induced negative effect sizes for other outcomes (e.g., Reeves & Chiang, 2019), suggesting that OPD can be more powerful for some outcomes over others.

As the studies included in the meta-analysis measure changes in these outcomes immediately after the end of the OPD program with a posttest, the high effect size could be partially explained by the fact that the posttest measures explicitly content from the OPD and is not, for example, a standardized test that measures more overarching concepts. This can result in a larger effect size. Also, testing right after the end of an intervention has been shown to draw larger effect sizes (Bailey et al., 2017).

On the classroom level, the participation of teachers in OPD that targeted changes in their classroom practice, like learning about better discussion strategies (Matsumura et al., 2019), yielded a medium effect size (Hedges' $g = 0.59$). This suggests that OPD programs are also successful in targeting outcomes on the classroom level and preparing teachers to change their teaching practices according to the content and input of the OPD. On the classroom level, only one outcome had a negative effect size of Hedges' $g = -0.08$ (Patel et al., 2018), while six had an effect size over Hedges' $g = 1.0$. On this level, the variance was not as high as on the teacher level, which might indicate that even though this level is less targeted, the structure and content of the OPD are more focused on eliciting positive changes for classroom practice. Factors such as the support system, intervention design, and the school context play a significant role in implementing interventions (Penuel, 2007), highlighting the complexity of translating PD program quality into direct classroom practice. My meta-analysis also reveals a promising trend: Although many of the included studies did not explicitly target implementation fidelity of the OPD, there is a noticeable change in classroom practices.

On the student level, changes or achievements were not as large as on the other levels (Hedges' $g = 0.21$), with no study showing an effect size over Hedges' $g = 0.59$ (Rose, 2012). According to Cohen (1992), an effect size of 0.2 is considered small, and one above 0.6 is large. Hattie (2012), however, states that the typical "hinge-point" of an intervention is an effect size of 0.4 *SD*, but even an effect size smaller than 0.4 also has real-life implications. Therefore, I conclude from the results that even though the effect on the student's level is smaller than on the teacher and classroom level, it can still be considered that the changes on this level were tangible and had real-life implications. Considering that changes on the student level are the most difficult to assess and that assessment can only happen if changes after PD participation have bled through all the other levels (Desimone, 2009), an effect size of 0.2 is still desirable. These results mimic other meta-analyses that investigated the effectiveness of in-person PD programs and generally found smaller effect sizes on the student level (Kraft et al., 2018; Yoon et al., 2007).

When testing Desimone's proposed core features, I found that not all the proposed features significantly influenced the effect sizes for OPD. The only exception was participation in collaborative learning activities that influenced outcomes at the classroom level. This finding contrasts most of the literature on in-person PD described in Section 1.2.2. Although other research has not found a conclusive statement about the core feature of duration, most in-person research agrees on the other four core features. For instance, Sims et al. (2021) found in their meta-analysis about characteristics of effective teacher professional development that the duration of the program was not associated with the outcome and effectiveness of the program (Basma & Savage, 2018; Kraft et al., 2018; Lynch et al., 2019). My findings suggest that for OPD, there might be other features in the foreground, which have to be investigated by future research in more detail.

In conclusion, the results of my meta-analysis suggested that participation in OPD is effective at all three outcome levels, with the teacher and classroom levels showing larger effect sizes than the student level, thus answering Research Question 1 (Chapter 2).

6.1.2 The Effects of Online Professional Development during Educational Reforms on Classroom Practice

As Section 1.1.1 highlighted, investigating PD participation (and, by extension, OPD) during educational reforms is crucial to ensure the implementation of reform efforts. Educational reforms pose a very strict universe in which changes must be implemented fast, and teachers fall under much stress to implement policies, especially if they are linked to high-stakes examinations like the AP exams in the United States. Therefore, Study 2 examined changes in teachers' concerns and classroom practices in the context of the AP Biology redesign in the United States. It also focused on the influence of OPD participation on concerns and practices. This longitudinal data analysis showed that teachers successfully adapted their classroom practices according to the AP redesign reform policies and that participating in PD was beneficial.

When investigating the impact of PD participation on teachers' perceived challenges with the reform, the results indicated that participation in PD did not decrease teachers' perceived challenges with the reform. This finding was against my expectations since previous research showed that PD programs can help teachers reduce their concerns (Margot & Kettler, 2019). The results suggested that the offered PD in Study 2 might not have been designed to reduce teachers' concerns. The focus on answering more practical questions, like how to design inquiry-based laboratory investigations, might have come to the foreground. However, other studies that have also investigated teachers' concerns during educational reform or curricula changes suggest that most teachers' perceived concerns change over time, even without participating in PD activities (e.g., Christou et al., 2004; Fischer et al., 2019; Geng et al., 2019).

Even though PD participation had no significant effect on teachers' concerns, I found a direct effect on teachers' classroom practices. The reform aimed to implement more labs and inquiry learning into classroom practice, and teachers were successful in doing so, as indicated by the increase in the number of labs and inquiry labs after three years. Teachers who participated in PD activities before the AP reform implemented more labs and inquiry learning into their teaching than teachers who did not participate. As mentioned previously, the teachers in the sample participated in the six-hour labs and inquiry learning workshop, a formal PD activity offered in two modalities: in-person or online. The goal of this PD activity was to inform teachers about the changes brought by the reform and focus on transitioning to inquiry-based learning labs with means to understand inquiry and its place in the classroom.

Thus, participating in these PD activities might have prepared the teachers already in the first year of the reform to implement more changes. The strong content focus of the workshop might have helped teachers better understand the reform, its purpose, and particular changes to classroom practice that it initiated. Importantly, whether the 6-hour workshop was delivered in-person or online did not make a difference in its effectiveness. This suggests that online PD could be a useful format in the future, given its benefits over in-person PD, like reduced costs for attendance, allowing more teachers to participate, and asynchronous participation (Dede et al., 2009; Fischer et al., 2019).

In contrast to the formal PD and OPD workshops offered to help teachers implement the AP reform, the College Board also offered the APTC, launched after the early AP science curriculum reforms one year before the AP Biology reform. It provided an informal space for teachers to share their experiences and questions with their colleagues and engage in discussion. In a study by Frumin et al. (2018), science teachers' participation in the APTC during the AP Chemistry, Physics, and Biology reforms was investigated. The results revealed that teachers with more teaching experience were significantly more likely to participate in the APTC, especially if they found the reform challenging. The authors argued that the APTC provided PD activities that were more effective than other PD activities offered by the College Board. Participants often emphasized the ability to ask personalized questions, share content, and be part of a supportive community, which was also suggested by previous literature to increase PD effectiveness (Section 1.3.4). The results suggest that being able to ask individual questions about inquiry labs in the APTC may have helped teachers incorporate more inquiry-based teaching. The APTC allowed them to exchange resources, tips, and experiences with their colleagues instead of just attending the formal 6-hour workshop.

Therefore, these results showed the potential for informal OPD participation in times of uncertainty, where "just-in-time" answers to questions and access to personalized information are highly beneficial for teachers (Romance & Vitale, 2001). Furthermore, it answered research question 2 (Chapter 2) by showing that OPD participation impacted classroom practices.

6.1.2 Informal Professional Development on Social Media

As highlighted in Section 1.3.4, informal OPD poses particular advantages and a vast potential for teacher PD. Study 3 examined the patterns of sharing educational resources on social media platforms, offering valuable insights into implementing educational resources in classrooms that teachers acquired through participation in informal OPD on social media. In Study 3, I presented a comprehensive overview of four key community types within the German X-sphere: the largest German teacher community, a chat-based community, a subject-specific community, and a community concerned with digital learning.

The findings revealed that educational resources were shared across all community types, with the digital learning community leading in total resource sharing, while EdChatDE exhibits the lowest. EdChatDE appears more focused on social connection and emotional support, with fewer media/links to educational resources. In contrast, being more topic-specific and unguided, the STEM and digital learning communities facilitated resource sharing based on individual needs. This aligns with the literature showing that different communities serve different purposes for their users (Fischer et al., 2023). Media types, such as links and photos, dominate resource sharing in all communities, while the popularity of other media types varies between communities.

Activity patterns across communities varied, emphasizing the common practice of users switching between communities. Despite this, positive sentiment prevailed in all communities, with teachers expressing more positive sentiment in their posts than non-teachers. The sentiment of replies to posts with educational resources did not consistently differ from posts without resources. However, in certain communities like TWLZ and STEM, teachers' replies to resource-sharing posts were more positive, indicating clearer expressions of appreciation.

While the ultimate goal of PD is to improve classroom practice and, ultimately, student outcomes, the study could not investigate the implementation of materials shared on X by questionnaire data or classroom observations. However, according to the Theory of Planned Behavior (Hall, 1973), strong intentions typically correlate with implementation. I observed a small percentage of posts indicating usage intentions in this study. For example, several posts displayed words such as "nutzen" (to use) and "implementieren" (to implement), suggesting a likelihood that these educational materials that the posts refer to would be employed in classroom practice.

In summary, this study gave a first insight into systemizing informal PD by analyzing sharing patterns of resources on social media data. Participation in social media is voluntary, and the analyzed data suggests that informal PD has been important for teachers for some time (Carpenter et al., 2013; Rosenberg et al., 2020). The COVID-19 pandemic might have catalyzed the participation, as the spike in the sharing patterns during 2019 in the TWLZ and digital learning community suggested. This aligns with a study by Fütterer et al. (2021) that showed many teachers turned to social media during the state-mandated lockdowns during the COVID-19 pandemic.

As previously mentioned, the study by Frumin et al. (2018) successfully linked the participation of teachers in the APTC with student outcomes, suggesting that teachers who participated regularly in the APTC had students with higher scores in the AP exams.

Together with the result from Study 2, one might suggest that participation in online community helped teachers improve their classroom practice. According to Desimone's framework, this improvement in classroom practice can benefit their students, too. However, this direct link between informal OPD participation and students' achievement can only be speculated, and more research on this has to follow.

Teachers could discuss innovations that will most likely impact their teaching practices on social media platforms in real-time. This immediate action would not be possible with formal

OPD or in-person PD programs since preparing formal workshops and courses takes more time (Section 1.3.1). The results of this study tied together with the results of Study 2 and implied that participation in informal OPD on social media could influence classroom practice.

In conclusion, by investigating and answering the two research questions, the dissertation provided a robust framework for understanding the multifaceted impact of OPD, thereby supporting its broader adoption and integration into more PD programs.

6.2 Strengths and Limitations

In empirical research, it is essential to evaluate both the strengths and the limitations to get a complete picture of its generalization and the situations where its results can be used. My dissertation, which looks into the effectiveness of OPD and the impact of informal OPD on classroom practice, also has its strengths and limitations. In the following subsections, I explained the conceptual and methodological strengths and limitations of the results and what it means for answering the research questions of this dissertation.

6.2.1 Conceptual Strengths and Limitations

A conceptual limitation that the results of this dissertation hold is the lack of a robust theoretical model that transcends all three studies. As I outlined in the first chapter of this dissertation, there are some theoretical frameworks and change models that explain the mechanisms of PD participation and its influence on the teacher, classroom, and student level, like the models from Desimone (2009, 2011) or Quinn et al. (2019). Desimone (2009) focused her model on a few empirical studies (including qualitative, case studies, and quantitative studies) that relied on the results of studies investigating formal in-person PD. In her later revision of the model in 2011, she extended the literature review and the model itself with a new focus, like the contextual features for PD participation. Moreover, the existing models are not comprehensive since they do not include all the possible PD formats that explain their characteristics and influence on participation outcomes. Consequentially, there is a lack of theoretical models that explain the mechanism of OPD participation. Furthermore, while Quinn et al. (2019) extended Desimone's (2009) model to OPD, it was primarily focused on formal OPD and the translation of the core features into the online context.

In addition, there is a complete lack of theoretical models that explain the effectiveness of informal PD for teachers, their classroom practices, and their student's achievement. This might be due to two reasons: First, educational research might have overlooked informal PD, with early studies emerging only in the 1990s (Clarke & Peter, 1993; Hodgson, 1986). In other fields like social sciences, informal learning in communities of practice and apprentices models have been studied more extensively (Lave & Wenger, 1991; Wenger, 1999, 2011), and most theories in educational science lean on these models. With the rise of social media and X, some researchers like Carpenter & Krutka (2014), Greenhalgh et al. (2020), and Rosenberg et al. (2020) have borrowed theoretical constructs from other disciplines like social sciences. For example, affinity spaces (Gee, 2017) and community of practice models (Wenger, 2011) were implemented into models of education science, explaining why teachers might seek these formats and how these activities benefit their learning.

The second reason, next to a lack of theories and empirical evidence, might be that informal learning is hard to quantify and measure in contrast to formal learning. Controlled experimental studies are complex to conduct as informal learning happens in spaces that are not organized or guided but instead are self-initiated by teachers. If there are studies that try to operationalize informal learning, they mostly rely on self-reported surveys. However, self-reports can be compromised by social desirability and response bias, leading to inaccurate or socially acceptable answers rather than reflecting the actual circumstances (Fowler, 2013; Podsakoff et al., 2003).

Despite these weaknesses, a strength of the dissertation is that it builds on the previous models of PD by introducing a two-dimensional conceptualization of PD with dimensions for modality and formality (Figure 3). This model allows researchers to operationalize PD and tie the four PD formats to certain activities, behaviors, and implications for classroom practice.

This categorization has been missing in the literature until now, especially in the theory-building of effective teacher PD. With the establishment of innovative possibilities for PD to be offered to teachers, newer and more comprehensive theories should consider PD's dimensions when conducting empirical research and making predictions about its effectiveness. Furthermore, the conceptual strength of this dissertation lies in its innovative approach to viewing OPD as an equal counterpart to traditional in-person PD and encouraging educational stakeholders and policymakers to acknowledge the dimensions as equally effective while considering the circumstances in which the dimension poses more advantage over the other.

6.2.2 Methodological Strengths and Limitations

This dissertation evaluates the effectiveness of OPD programs, considering both formal and informal OPD and employing a variety of robust and innovative methodologies to unravel the impacts of OPD participation on teachers, their classroom practice, and students. As with every quantitative research, the studies included in this dissertation have some methodological limitations, primarily rooted in the quality of the methodological design and the data used for analysis.

The meta-analysis (Study 1), while providing a powerful measure of effect sizes, depends on the quality of the included studies. Many studies lacked rigorous designs, relying predominantly on within-subject measures without control groups, making it difficult to assess the effectiveness (Greenwald, 1976). Even though the moderator analysis included in this study showed no significant influence of the study design on the effect size results, one cannot rule out that results from studies with an RCT design are conceptually and methodologically stronger than simple within-subject design and should, therefore, be encouraged more in research (Greenwald, 1976). Furthermore, another limitation of the meta-analysis is that it combines all outcomes across the levels investigated in the included studies, resulting in a high heterogeneity of the results. These outcomes should be disentangled and grouped into individual meta-analyses for future research. However, this is only possible when more research on each outcome exists so that more than the recommended minimum ten effect sizes can be grouped (Borenstein et al., 2021). Furthermore, even though extensive, the database for the meta-analysis from 2005 to 2019 is not exhaustive because newer studies, after and during the COVID-19 pandemic, have not been considered in the analysis yet.

Even though subject to some limitations, conducting a meta-analysis is generally one of the best methods to derive empirical evidence, robust measures, and the most accurate effect sizes of intervention studies (Borenstein et al., 2021). By aggregating the sample size of included studies, the statistical results yield a higher power, allowing more robust conclusions (Cooper, 2015) and introducing moderators to discern the influence of specific study or design characteristics (Littell et al., 2008). In the meta-analysis (Study 1), 85 studies were included with 215 effect sizes in total (186 effect sizes on the teacher-, 32 effect sizes on the classroom, and 33 effect sizes on the student level) and a sample size of 22,213 teachers and 18,239 students. The large number of participants and effect sizes give the most comprehensive results for the effectiveness of OPD participation to date.

The methodological limitations of Study 2 are also related to the data sources. The data was limited to teachers' self-reports, which might threaten the validity of the results, as it has been shown that self-reported data, in most cases, are not the most reliable (Fowler, 2013; Podsakoff et al., 2003). In the study, I also treated Likert-type data as continuous data, which assumed an equal distance between the response categories (Carifio & Perla, 2008) that was not controlled for. Furthermore, there might be some selection bias within the data since highly motivated teachers might have participated more in the PD opportunities than other teachers. Also, no additional data was available to investigate teachers' motivation types. Generally, as the sample only included AP teachers, it is not possible to generalize the results to the overall teacher populations, as AP Biology teachers are the most qualified teachers in the United States, which is reflected in their degrees (Fischer et al., 2018). As Fischer et al. (2018) have pointed out, the study could provide a "best practice" example with teachers who are the most qualified and prepared to respond to an educational reform.

Even though the data source might have limitations, investigating a longitudinal dataset using latent growth curve modeling poses several advantages over other analysis methods, such as ANOVA. For example, growth curve models enable the modeling of individual trajectories of change, allowing them to capture an average trend and the variability within data (Duncan et al., 2013). Furthermore, they also account for measurement errors and provide more accurate and reliable growth parameter estimates than traditional repeated measures ANOVA (Curran et al., 2010). Another advantage is that time-invariant and time-varying covariates can be incorporated, allowing for examining factors that influence growth or change over time, like PD participation. Additionally, growth curve models can handle incomplete data more effectively through maximum likelihood estimation, reducing bias and improving the validity of the findings (Enders, 2013). Therefore, these methods provide more robust statistical insights into a longitudinal change in teachers' concerns and classroom practice over three years of reform implementation.

Like the other studies, some methodological limitations for Study 3 also include the data basis. Although this is the most extensive dataset of the three dissertation studies, with 2,064,799 posts from 116,967 users, it is still limited in scope since it spans from 2008 to 2020. Furthermore, even though the dataset was able to catch the most crucial phase of the COVID-19 pandemic, when many teachers turned to social media like X (formerly known as "Twitter") for help and support (Fütterer et al., 2021), data from new tools like the introduction of ChatGPT is missing. Other methodological limitations included the classification of teachers, for which the teacher's bios on X and 50 of their posts were used to train an automatic classifier. Some teachers might not have been classified correctly using only these parameters since they did not indicate anything in their bio, leading to a smaller sample than the underlying data suggests. Overall, only data from the teachers who participated actively in the online communities were available. The data from so-called "lurkers" (Fischer et al., 2019) were inaccessible. These users consume the content and might even incorporate materials in their classroom practice but do not post this on X. For the overall population, we can, therefore, only make assumptions until a stronger method arises to catch their behavior as well. Due to ethical concerns, I could not analyze the content of shared links and media, leaving me with only being able to make assumptions about the nature of shared materials. Furthermore, although analyzing teachers' behaviors based on intentions was innovative and grounded in theory, it still draws an inconclusive picture of the actual implementation into classroom practice. Having additional self-reported or experimental data about material usage would strengthen the results.

Nonetheless, this research offers new perspectives on the sharing patterns of educational resources on social media platforms. It sheds light on integrating educational resources into classroom practices and their practical utility for teachers. By examining four key community types within the German X-sphere, I provide a comprehensive overview of the most significant online communities for the informal sharing of educational resources. Through big data analysis, this study sought to enhance methods in educational research, moving beyond the traditional reliance on questionnaires and self-reported teacher data. Additionally, this study establishes direct connections between Desimone's model of effective teacher professional development (Desimone, 2009) and the Theory of Planned Behavior (Ajzen, 1991), exploring how teacher-level variables such as sharing behavior, sentiment, and popularity influence their classroom practices through the intended use of educational resources they found online. Ultimately, the study shows us that informal OPD on social media is something teachers frequently engage in and might also have implications for their classroom practice.

To summarize the strengths and limitations of the three studies, even though the data source might be limited in scope and is subject to the usual problems of validity of empirical research, the results of this dissertation evaluate the effectiveness of OPD using various robust and innovative methods. The results collectively highlight the importance of OPD participation and reveal how it supports teachers' knowledge and improves classroom practices that potentially enhance student outcomes.

6.3 General Implications and Future Directions

6.3.1 Implications for Practice

This dissertation answered two research questions that are highly important for policymakers, practitioners, teachers, and other researchers.

First, we confirmed that participation in OPD was effective for teachers and induced changes in their knowledge, skills, attitudes, beliefs, and classroom practice. Importantly, their students also benefitted from their OPD participation. This implies that OPD participation should be encouraged by teachers since it poses several advantages compared to in-person PD, such as greater accessibility, reduced costs, learning at one's own pace, and more individualized learning opportunities (Carpenter & Krutka, 2014; Dede et al., 2016; Fischer et al., 2019; Fütterer et al., 2021). Furthermore, when designing OPD courses and workshops, we advise PD providers and researchers to not only focus on outcomes at the immediate teacher level. Although the teacher level is the most accessible level, there should also be an increased focus on acquiring more tangible skills or materials that teachers can implement in their classroom practice or when working with students. Moreover, we aim to encourage educational stakeholders to consider features such as opportunities for collaborative and active learning and the mode of delivery (synchronous/asynchronous), as these features are more effective for OPD than others (Study 1).

Secondly, Studies 2 and 3 also confirmed the important role of informal OPD for teachers and their classroom practices. Informal OPD is especially beneficial in times of uncertainty, and many teachers already participate in self-directed informal learning (Carpenter et al., 2014; Fütterer et al., 2021). Therefore, practitioners should try to leave their skepticism of informal OPD behind, educate teachers about the possibilities this dimension of PD poses to them, and encourage participation. With numerous advantages over traditional in-person formats, informal OPD can effectively elevate the PD experience through different formats like blogs, forums, and social media. Especially these informal learning activities and the formation of communities of practices should be encouraged so that change and OPD can be more sustainable and long-lasting, as some research suggests (Carpenter & Krutka, 2014; Fischer et al., 2023; Rosenberg et al., 2020).

I also highlighted the classification of PD within two dimensions that differ in formality and modality. This might help practitioners map their PD program, select activities, and design features for different purposes. For example, incorporating additional informal OPD features to their formal in-person PD program could elevate teachers' PD experience so that a larger variety of PD modes can be offered.

6.3.2 Implications for Research and Future Directions

The dissertation cannot answer all relevant open questions in the field of teacher PD. However, it helps to pave the way for more informed research questions and opens a debate on how (informal) OPD can be assessed and further analyzed. First of all, the proposed model of PD dimensions can be implemented in further research that emphasizes and focuses on the PD dimensions and manipulates them in experimental settings so that each PD format's effectiveness can be assessed and isolated. Another possibility could be that the PD formats can be coded as moderators in an even more comprehensive meta-analysis that includes in-person PD and OPD.

Another implication for research might be encouraging more researchers to conduct RCTs to investigate the effects of OPD participation. Only the minority of studies included in the meta-analysis used an RCT design, and no studies have used RCT designs when investigating informal OPD. RCT studies are the most robust study design to discern intervention effects, compared to a randomly assigned control group that did not receive the intervention. Based on the randomized nature of choosing which participant is classified into either an intervention or control group, bias in the sample can be reduced (Schulz et al., 2010). This makes statistical results even more robust. Therefore, researchers should be encouraged to design more RCT studies. Universities, research centers, and educational stakeholders should be encouraged to invest more resources, like monetary resources and staff, to conduct these studies. Moreover, longitudinal study designs should be used since conducting long-term studies to assess the sustained impact of OPD on teacher practice and student outcomes would provide valuable insights into the long-term effectiveness of OPD participation, as shown by Study 2.

Furthermore, the dissertation results suggest that Desimones' (2009) core features can not be generalized for all four PD formats and must be investigated more rigorously through experimental manipulation rather than literature reviews. Specific core features for OPD, notably for informal in-person and OPD, are missing. Teachers' motivation is another important but often overlooked factor that influences in-person PD and OPD participation, as I have stated in Chapter 1.1. When teachers face external circumstances, like educational reforms, their motivation to participate in OPD might be higher because the pressure of implementing change is stronger. When looking into voluntary participation, it is often the more motivated, already well-performing teachers that have a more intrinsic motivation to participate in OPD. Research should consider the internal factors of teachers and offer OPD programs according to their needs, circumstances, and motivation type so that even more teachers can be targeted and profit from OPD participation, which is the most beneficial for them. To address these biases and to ensure more inclusive and equitable PD practices, it is important to adopt strategies that actively engage all teachers, regardless of their initial motivation or proficiency levels. This may involve providing targeted support, reducing barriers to participation, and fostering a culture of continuous learning within educational settings (Kennedy, 2016).

Furthermore, more blended PD approaches can be investigated. Blended PD is the mix of in-person PD activities, like workshops, and OPD activities, like online courses or participating in forums and chatrooms. With a mix of both dimensions, PD programs can be even more adaptive to specific needs and combine the advantages of both, like meeting colleagues in person but still having the flexibility to ask questions to a wider audience through social media.

With the rise of newer social media sites like Instagram and TikTok and the mass introduction of virtual reality and artificial intelligence, it is important to investigate further the role of social media platforms in facilitating informal OPD and fostering professional learning communities that could help leverage these tools for more effective teacher support and collaboration.

Finally, translating the findings of this dissertation into actionable policy recommendations could help educational stakeholders make informed decisions about the design, implementation, and evaluation of OPD initiatives.

6.4 Conclusion

Online professional development (OPD) has become an important venue for teacher professional development (PD) in recent decades due to several advantages over traditional in-person PD. While most research and conceptual models have focused on in-person PD, there remains an opportunity for a comprehensive investigation into the effectiveness of OPD.

This dissertation, therefore, answered two research questions: First, how effective is OPD generally for teachers, classroom practice, and student achievement? And second, how can informal OPD participation support teachers' classroom practice? The results of a meta-analysis revealed that teachers' OPD participation had a medium effect on their knowledge, skills, attitudes, and beliefs, a medium effect on their classroom practice, and a small effect on students' achievement. Thus, it challenges the traditional view that only in-person PD can be effective and provides evidence-based support for the effectiveness of OPD participation.

The results from longitudinal data in the context of a nationwide reform in the United States shed light on the significance of OPD participation in supporting teachers during educational reforms. Social media data suggested that teachers participate in informal OPD to find educational resources for classroom practice. These studies revealed the great potential of informal OPD participation for teacher and classroom practice outcomes.

By categorizing teacher PD into two dimensions that differ in formality (formal and informal) and modality (in-person and online), this dissertation was able to give new insight into how research and practitioners can categorize teacher PD. Therefore, the results reveal important implications for research and practitioners, encouraging them to implement more OPD opportunities for teachers and pushing the frontiers of teacher learning into more innovative forms of PD.

7

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7 References

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8

Appendix

8 Appendix

Declaration of Authors' Contribution

This dissertation is publication-based and includes three manuscripts written together with other authors. The proportional contributions to the manuscripts are presented in the following tables.

Chapter 3

Study 1: Effects of Online Teacher Professional Development on the Teacher, Classroom, and Student Level: A Meta-Analysis

Author	Author position	Scientific ideas %	Data generation %	Analysis and Inter-pretation %	Paper writing %
Fitore Morina	First	40	100	70	75
Tim Fütterer	Second	25	0	0	5
Nicolas Hübner	Third	5	0	0	5
Steffen Zitzmann	Forth	5	0	20	5
Christian Fischer	Fifth	25	0	10	10

Status of the publication process: Revise and resubmit

Chapter 4

Study 2: Examining Laboratory Investigations in Advanced Placement Biology: Teachers' Perceived Challenges and Their Classroom Practice

Author	Author position	Scientific ideas %	Data generation %	Analysis and Inter-pretation %	Paper writing %
Fitore Morina	First	60	0	80	70
Nicolas Hübner	Second	5	0	20	10
Arthur Eisenkraft	Third	0	100	0	10
Christian Fischer	Fourth	35	0	0	10

Status of the publication process: Submitted

Chapter 5

Study 3: Unlocking the Potential of Educational Resources: An Examination of Sharing and Usage Patterns in Educational Online Communities

Author	Author position	Scientific ideas %	Data generation %	Analysis and Interpretation %	Paper writing %
Fitore Morina	First	75	20	90	80
Tim Fütterer	Second	10	0	0	5
Joshua Rosenberg	Third	5	0	5	5
Jeffrey Carpenter	Fourth	5	0	5	5
Christian Fischer	Fifth	5	80	0	5

Status of the publication process: In preparation.