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A Meta-Analysis of Reform-based Professional Development in STEM: Implications for Effective Praxis

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Abstract

A systematic review and meta-analysis was conducted to examine the effects of reform-based professional development on mathematics and science teachers Pedagogical Content Knowledge (PCK). An exhaustive literature search returned 15 studies, from which 21 independent effect sizes were extracted. These studies included, K-12 pre- and in-service mathematics and science teachers as participants (N = 1,044). The mean overall effect size was statistically significant ($d = 0.51$, $p < 0.001$). Heterogeneity analysis revealed consistency throughout the studies based on a non-significant value for the Q statistic. This suggests that the variance between studies was not more than what would be expected by random error. The variation in study characteristics warranted an examination of possible moderators, despite the absence of statistically significant heterogeneity. Teacher type (in-service vs. pre-service), subject (mathematics vs. science), and outcome measures were all non-statistically significant moderators of the effect size. The results of this study are substantial because they suggest that the effects of reform-based professional development are consistent across settings and teaching populations. Additionally, this suggests that the relationship between reform-based professional development and PCK are robust. Other implications and recommendations for professional development to maximize opportunities to learn in STEM classrooms are also provided.

Introduction

Pedagogical content knowledge (PCK) is an enduring construct related to the preparation and efficacy of Science Technology Engineering and Mathematics (STEM) teachers. The importance of this construct is apparent in the many reformations and adaptations across educational disciplines (Kleickmann et al., 2013; McNeill, González-Howard, Katsh-Singer, & Loper, 2016). As this construct evolved it became synonymous with "teacher quality". Subsequently, a need to measure this construct was warranted. A central issue in measuring teacher quality is the validity of using one's content knowledge as a primary factor to determine if one is a "highly-qualified teacher." Several systematic reviews and meta-analyses have assessed in-service and pre-service teacher PCK across its variants in an effort to examine intervention effects on teacher quality (Author, 2013; Rowan et al., 2001; Seidel & Shavelson, 2007). Many of these studies were funded and supported by policy demands.

Educational policies continue to place more attention on the development and measurement of PCK as an appropriate instructional intervention. Under No Child Left Behind (NCLB), grants for content focused mathematics and science teacher professional development were awarded (NCLB, 2002, p. 114). While, the Every Student Succeeds Act (ESSA) addressed this lack of pedagogical focus by strategically using the term "effective teaching" to replace the controversial term "highly-qualified teacher" dominant in NCLB. These changes were also reflected in mathematics and science teaching association documents. The National Council of Teachers of Mathematics (NCTM) calls for equitable access to high-quality mathematics curriculum and instruction (NCTM, 2012, 2014).

Likewise, the National Science Teachers Association (NSTA) emphasizes "quality science education for *all* students" (NSTA, 2010, p. 1). A more balanced approach to the preparation and continued development of mathematics and science teachers was a result of these trends in educational policy. Both NCTM and NSTA encourage educators to continue professional development and stay current on reform practices to maximize learning opportunities for students in mathematics and science classrooms. As a result of the aforementioned policy requirements professional development and continuing education efforts increased. However, the level of in-service and pre-service teacher PCK remains a concern for parents, teacher educators, and school leaders.

Purpose

In order to make sound and effective instructional decisions researchers, teachers, and instructional leaders need comprehensive evidence to support or refute the effectiveness of professional development efforts. Despite its necessity, an examination of the effects of reform-based professional development on STEM teacher PCK remains relatively absent in the literature. The purpose of the present study was to summarize the effects of reform-based professional development on mathematics and science teachers' PCK. This study is guided by the following two questions:

1. What is the effect of professional development activities on in-service and pre-service, mathematics and science teachers' PCK?
2. How are these effects moderated by: teacher type, subject, and outcome measure?

Literature Review

Currently in mathematics and science teacher professional development, researchers are interested in defining and analyzing what is meant by "effective" professional development. In mathematics teacher education, current research efforts focus on the effects of policy on teaching and teacher quality (e.g., Jacob, Hill, & Corey, 2017; Hill, Beisiegel, & Jacob, 2013; Hill, 2010; Hill, Ball, & Schilling, 2008). In science teacher education, studies dedicated to the promotion of effective instruction in teaching science through the lens of scientific literacy (e.g., Bybee, 1997; Bybee, et al., 2006; Bybee, 2013). These finds offer credence to discussions regarding STEM education, and were instrumental in the drafting of the Next Generation Science Standards which infuses scientific enactments into classroom instruction (Bybee, 2011; NRC, 2012). These standards reflect specific subject matter knowledge necessary for teachers to be effective instructional leaders.

Teacher knowledge of specific subject matter and how to teach the subject matter to promote student learning are essential considerations for effective teacher development. Originally conceptualized by Shulman (1986), PCK lies at the intersection of pedagogy and content. Teachers capitalize on students' diverse thinking and knowledge of a specific subject area to adjust instruction and impact student learning. Scholars have expanded on Shulman's (1986, 1987) initial concept to further theorize and provide empirical evidence for the PCK construct. For example, Ball, Thames, and Phelps (2008) theorize *specialized content knowledge* (p. 390) from Shulman's PCK to address a "pure" knowledge of subject-matter that does not involve knowledge of the learners, and is only used in the act of teaching. In the sections that follow the development and measurement of PCK in mathematics and science is discussed.

Ball et al. (2008) refine Shulman's work to reflect the nuances of mathematics classroom interactions. The mathematics knowledge for Teaching (MKT) is divided into two domains: an adapted version of PCK and subject matter knowledge (SMK). To accompany this framework the researchers also provide assessments to measure the effectiveness of professional development programs. For example, Hayata's (2012) study involved undergraduate pre-service elementary teachers enrolled in a teacher preparation program at a large university. Specifically, Learning Mathematics for Teaching (LMT) was used to measure student-teachers' mathematical knowledge for teaching (MKT) at five time points during the last year of the teacher preparation program. Results suggest a slight increase in MKT measures on number sense while enrolled in a semester long math methods course, and then a greater decrease during the following semester in which pre-service teachers were in student teaching placements.

In contrast to viewing PCK as an outcome measure, Loughran, Mulhall, and Berry (2008) studied the learning of PCK in science education programs. To gain insight in the complexities of student learning, Loughran and colleagues use PCK as a heuristic means to help student-teachers better conceptualize and understand the professional knowledge necessary to become an effective science teacher. Upon entering a teacher education program, student-teachers' schema of teaching involves 'teaching as telling' and therefore expect to be told how to teach. In explicitly teaching student-teachers about PCK, findings suggest a transformation in student-teacher beliefs from seeing PCK as an educational theory to the practicality of developing their professional knowledge (Loughran et al., 2008). Other studies provide additional context and perspective to the discussion.

Banilower, Boyd, Pasley, & Weiss, (2006) conducted a comprehensive study of professional development programs within the nationwide Local Systemic Change (LSC) project on pedagogies and beliefs in addition to content knowledge. Findings suggest a positive impact on teaching and learning, particularly in regards to teachers' attitudes towards educational reform in mathematics and science education. Also, evidence of scaling-up the use of high-quality materials and providing supportive infrastructures at the district level has been reported by participating school districts. However, LSC programs found challenges in addressing the content needs of teachers. For example, local teacher leaders lacked the necessary content knowledge to aid their colleagues specific content needs. This small-scale meta-analysis contributes to the body of work conducted by others. All of these studies have led to the reform-based policies reflected in current science and mathematics standard documents. The framework for K-12 science education (NRC, 2012) includes practices for both science and engineering. Similarly, NCTM (2014) issued a set of effective mathematics teaching practices. These two sets of instructional strategies elicit student thinking in ways that mimic how scientists (engineers and mathematicians included) work in their professional fields. Hence, professional development for teachers in STEM fields is shifting toward an emphasis on these practices, keeping the target of both content and pedagogy as the focus. These reformed based strategies and ideas are the objective of the current study. In the section that follows the analytical procedures used to address the aforementioned research questions are further elucidated.

Method

This meta-analysis was conducted in several steps in an iterative process. The literature search began with a full search in relevant databases (EBSCO Host, JSTOR and ProQuest Dissertations and Theses). A combination of key terms and phrases were used to identify possible studies. For example, key terms and phrases included *pedagogical content knowledge, mathematics, science,* and *professional development*. Based on titles and abstracts, an initial 63 articles were examined. Seventeen articles were removed based on their abstracts leaving 46 studies for full review.

Criteria for Inclusion

The studies included followed three main constraints to limit inclusion to professional development programs focusing on PCK. The methodology section was reviewed and of the 46 studies, 15 qualitative studies were removed leaving 31 studies for further examination. Second, the outcome measure must have been categorized as either content knowledge (CK) or pedagogical content knowledge (PCK). Content knowledge was considered as an outcome measure only because the professional development focused on enhancing one's pedagogical knowledge. Lastly, participants must have been K-12 teachers at the time of the study. Both pre-service (PST) and in-service (IST) teachers were included for this meta-analysis. An additional 15 studies failed to meet the three constraints. Studies focusing on enhancing content knowledge only, measuring student achievement or measuring attitudes and beliefs were all excluded from the present meta-analysis study. The 16 studies satisfying the three constraints are listed in Table 1.

Coding

The attributes of each code were established iteratively throughout the review process. After consideration of all articles, the codes were finalized, and all items were coded. During the coding phase, one study was excluded from the initial set of screenings. The study compared novice teacher's PCK to experienced teacher's PCK and did not directly include a form of professional development. A second rater independently coded a random selection of five articles. Cohen's κ was calculated as a measurement of interrater agreement on categorical data while Pearson's r was calculated for continuous numerical codes. For categorical codes, Cohen's κ was measured at 0.81 while Pearson's r was measured at 0.93 for continuous codes. The attributes of each code are described below.

Study Characteristics

Studies were categorized as a journal, dissertation or conference proceeding. Seven of the fifteen studies (47%) were classified as journal publications while seven studies were categorized as doctoral dissertations. All dissertations included in this meta-analysis were unpublished and were found in the ProQuest Digital Dissertations database. One study (7%) was categorized as a conference proceedings publication. The studies were categorized as either mathematics or science. Of the fifteen studies, four (27%) were science while eleven studies (73%) included mathematics teachers. The teacher type and grade band codes addressed the participants of the research. Nine studies (60%) included in-service teachers while six studies (40%) included pre-service teachers. In terms of grade band, nine studies (60%) included elementary teachers while six studies (40%) included secondary teachers. Of the six secondary teachers, three were also in-service teachers. Three main assessment tools were identified for coding: Learning Mathematics for Teaching ([LMT], Hill & Ball, 2004), Essential Elements of Elementary School Mathematics ([EEESM], White, 1986), and the Reform Teaching Observation Protocol ([RTOP], Sawada et al., 2002). All other assessment tools were categorized as researcher made assessments. Hill and Ball (2004) developed LMT measures to assess both content knowledge and pedagogical content knowledge of mathematics teachers expanding on Shulman's (1986) integrated model. Also in 1986, White's doctoral dissertation describes the development and validation of the evaluation instrument, EEESM to specifically measure the mathematics achievement of pre-service elementary teachers. Sawada and colleagues (2002) developed the RTOP to observe reform teaching practices of science teachers.

The assessment type was coded as multiple choices, open ended, or observation assessments. While reading the studies, studies such as Bell et al. (2010) emphasized whether or not the assessments used were multiple choice or open-ended. In that particular study, the researchers chose to use both types of assessments resulting in two effect sizes for this meta-analysis. The outcome measure was categorized as either CK or PCK. Of the 21 effect sizes calculated in this meta-analysis, 7 effects (33%) were coded as CK, while 14 effects (67%) were coded as PCK. For each study, the value of Cohen's *d* was calculated using Wilson's (2001) online practical meta-analysis effect size calculator. With the exception of two studies (Hayata, 2012; Polly, Neale, & Pugalee, 2014), the means and standard deviations calculator were used based on pre- and post-results for within-subjects studies and post-results of control and treatment groups for quasi-experimental studies. In Hayata's (2012) study, the effect size was calculated based on the reported chi-squared value while the p-value and t-test results were used to calculate the effect size for Polly and colleagues' (2014) study.

Table 1. Attributes of Included Studies

Study	*Publication Type*	*Measurement*[1]	*Assessment Tool*	*N*	*Effect size*	*Outcome Measure*	*Subject*	*Teacher Type*	*Grade Band*
Bell, et al. (2010)	Journal	MC	RM	179	0.38*	CK	Math	IST	Elementary
	Journal	OE	RM	179	0.52*	PCK	Math	IST	Elementary
Diaconu, et al. (2012)	Journal	MC	RM	57	0.89*	CK	Science	IST	Elementary
	Journal	MC	RM	60	0.59*	CK	Science	IST	Elementary
Evans (2011)	Journal	OE	RM	42	0.61*	CK	Math	IST	Secondary
Gray, Webb, & Otero (2010)	Conference	Ob	RTOP[2]	[19,20] [3]	0.75*	PCK	Science	PST	Secondary
Harr, Eichler, & Renkl (2014)	Journal	OE	RM	[31,29]	0.73*	PCK	Math	PST	Secondary
Hayata (2013)	Dissertation	MC	LMT [4]	176	0.46*	PCK	Math	PST	Elementary
Kramarski & Revach (2009)	Journal	OE	RM	34	0.75*	CK	Math	IST	Elementary
Matthews (2006)	Dissertation	MC	RM	[42,22]	0.44	CK	Math	PST	Elementary
Monet (2006)	Dissertation	OE	RM	10	1.51*	PCK	Science	IST	Secondary
Polly, Neale, & Pugalee (2014)	Journal	MC	LMT	28	1.40*	PCK	Math	IST	Elementary
Schectman, et al. (2010)	Journal	MC	LMT	47	0.57*	PCK	Math	IST	Secondary
Strawhecker (2004)	Dissertation	MC	EEESM [5]	28	0.27	PCK	Math	PST	Elementary
	Dissertation	MC	EEESM	15	0.50	PCK	Math	PST	Elementary
	Dissertation	MC	EEESM	36	0.63	PCK	Math	PST	Elementary
Turner (2011)	Dissertation	Ob	RTOP	[56,35]	0.06	PCK	Science	IST	Elementary
Van Steenbrugge et al (2014)	Journal	MC	RM	[197,93]	0.63*	CK	Math	PST	Secondary
Waller (2012)	Dissertation	MC	LMT	142	0.33*	PCK	Math	IST	Elementary

*p<0.5

[1]For the *Measurement* construct, the codes are as follows: MC→Multiple Choice; OE→Open-Ended; and Ob→ Observation

[2]The Reform Teaching Observation Protocol (RTOP) was used to measure PCK of a treated group vs. a control group.

[3]In this study *N* represents the number of observations completed for 7 teachers in the experimental group vs. the 7 teachers in the control group. In all other studies, *N* represents the number of participants in the study. A single *N* represents one group assessed for pre-and post-measures. Bracketed *N* indicates an experimental group and a control group.

[4]Learning Mathematics for Teaching

[5]Essential Elements of Elementary School Mathematics

Also, three studies provided more than one effect size, and each was disaggregated for this meta-analysis. Two of the studies (Diaconu, Radigan, Suskavcevic, & Nichol, 2012; Strawhecker, 2004) used independent groups resulting in effect sizes for each independent group. Conversely, Bell, Wilson, Higgins and McCoach (2010) used two different assessment types resulting in two effect sizes for the same participants. The mean effect size for the one study was not calculated according to Rosenthal and Rubin's (1986) procedures; however, the lack of independent participants was addressed when using the Comprehensive Meta-Analysis software.

Analysis

For this meta-analysis, version 3.0 of the Comprehensive Meta-Analysis software was used to calculate all statistics relevant to this study. The weighted mean effect size and confidence intervals were calculated and graphed (see Figure 1). Then, We completed a homogeneity analysis to ascertain whether or not the distribution of effect sizes could be attributed to differences beyond subject-level sampling error (Lipsey & Wilson, 2001). The Q and I^2 statistics were used to determine homogeneity. We chose to investigate three moderators (teacher type, subject, and outcome measure) for statistically significant differences to confirm the homogeneity of the mean effect size of the data set. Lastly, Rosenthal's (1979) fail-safe N was calculated to address any potential publication bias issues. For this meta-analysis, three moderators : subject, teacher type, and outcome measure.

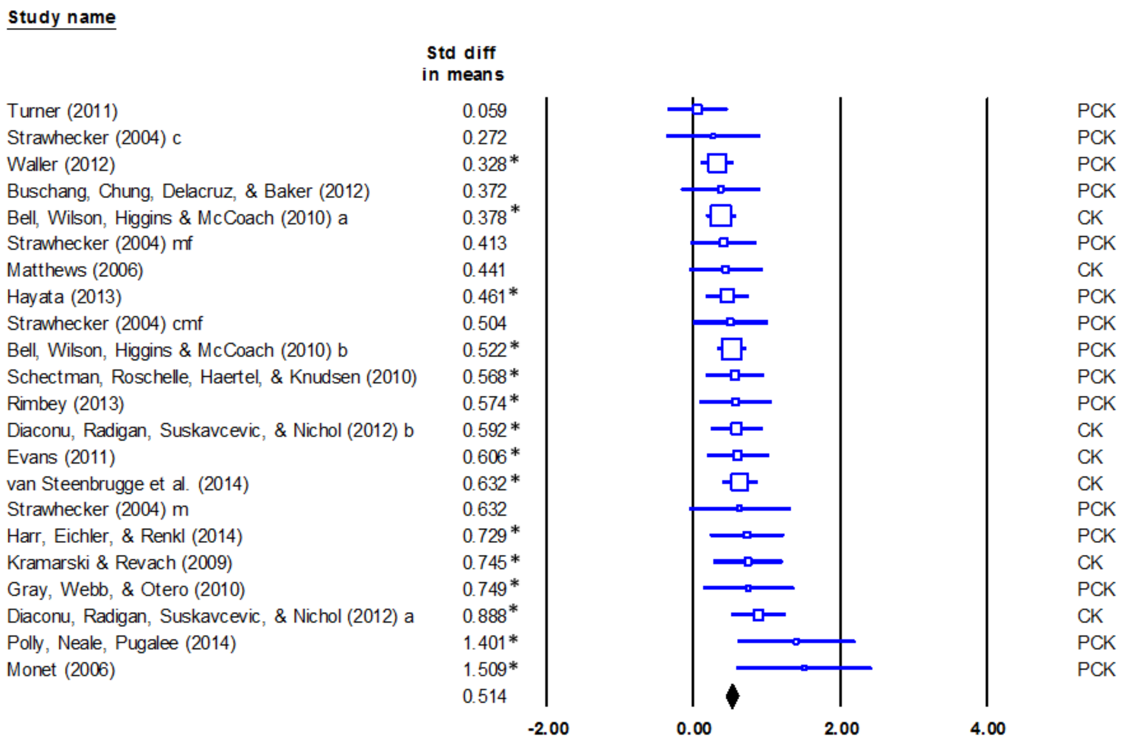

Figure 1. Forest Plot of Included Studies

Results

The attributes of each of the studies are outlined in Table 1. As previously mentioned, there is an even balance between published and unpublished studies (seven each, and also one conference proceeding). However, there are more math studies than there are science studies included in this meta-analysis. Of the fifteen studies analyzed, a total of 21 effect sizes were extracted for use in this meta-analysis. The overall mean effect size for professional development on the change of one's PCK is 0.51, $p < .001$.

Homogeneity

The 21 effect sizes and confidence intervals are graphed in Figure 2. Larger squares indicate a larger weight assigned to the effect size due to a larger sample size. The overlapping confidence intervals confirm the homogeneity of the studies as determined by the Cochran's Q and Higgins' I^2 statistics. The Q statistic was not significant, and therefore indicating a lack of heterogeneity, $Q(20) = 26.17$, $p = 0.16$. However, Higgins and colleagues (2003) argued fallibility in the use of Cochran's Q for determining homogeneity. The I^2 statistic provides a quantifiable measure of heterogeneity. For this study, $I^2 = 23.57$, suggesting approximately 23.57% (low value) of variance between studies cannot be attributed to chance. Despite initial statistical indications of homogeneity amongst the studies it was imperative to substantiate these statistical results. Given that pre-service and in-service teachers represent two distinct populations and that science and mathematics are also very different content areas it is reasonable to assume that variation exist across these moderators.

Moderators

Table 2 outlines the results of the moderator effects analysis. The Q_{between} statistic was not significant for each of the three moderators: teacher type, subject, and outcome measure. This confirms the homogeneity across all studies. The effect sizes of each group within a moderator type were all significant. However, they were not found to be statistically significantly different from each other.

Table 2. Moderator Analysis

Moderator	*k*	Q_B	Effect Size	95% Confidence Interval
Teacher Type		**0.36**		
In-Service	12		0.49*	[0.39, 0.60]
Pre-Service	9		0.55*	[0.41, 0.689]
Subject		**1.08**		
Math	16		0.49*	[0.40, 0.59]
Science	5		0.61*	[0.41, 0.82]
Outcome Measure		**0.87**		
CK	7		0.56*	[0.44, 0.68]
PCK	14		0.48*	[0.38, 0.59]

Publication Bias

Lipsey and Wilson (2001) caution analysts of the potential bias towards statistically significant effect sizes due to the accessibility to published studies which typically generate larger mean effect size. For this meta-analysis, we included both published journal articles, unpublished dissertations, and conference proceedings. Using the Comprehensive Meta-Analysis software, a funnel plot was generated to analyze the plausibility of missing or unrepresented studies. Figure 2 shows the funnel plot diagram for this study.

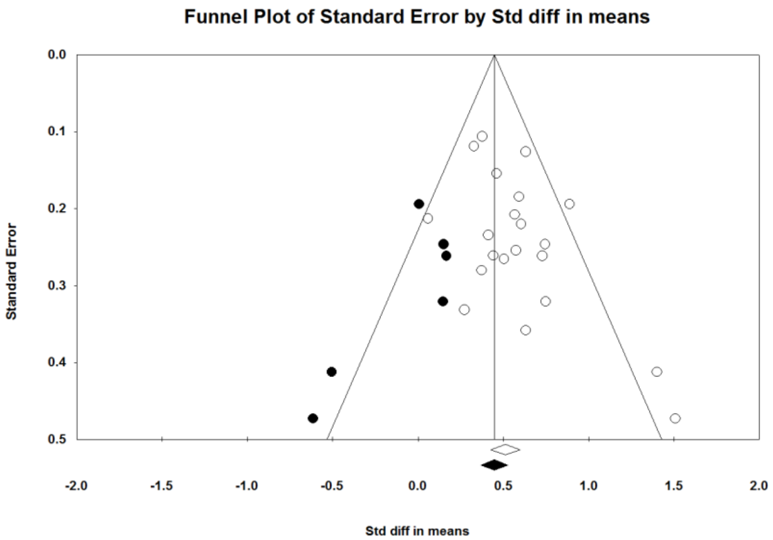

Figure 2. Publication Bias Funnel Plot

The open data points represent the studies observed in this meta-analysis while the six closed data points represent the potentially unrepresented studies that would symmetrically balance the diagram. Symmetrically distributed studies indicate the absence of a publication bias. For this study, the six trim and fill data points shift the mean effect size only slightly to the left. In addition to the funnel plot, Rosenthal's (1979) fail-safe N was calculated to determine the approximate minimum number of studies necessary to statistically significantly alter the mean effect size. In this study, 742 studies would be required to shift the average effect size of the data set.

Discussion

For this preliminary meta-analysis, the aim was to investigate the change of mathematics and science teachers' PCK after participating in a professional development program focusing on reform practices. The overall results suggested a medium effect size implying a change in one's PCK, but only a moderate change. However, a disaggregated view of all the studies and effect sizes with each of the studies reveals a broad range of effects from 0.60 to 1.51. Also, while the heterogeneity measure was a low 24%, differences exist in the data set. Because of the small number of studies included in this study, they may skew the findings. For example, Figure 1 displays two studies on the upper end (Polly, Neale, & Pugalee, 2014; Monét, 2006) and one study on the lower end (Turner, 2011) that have the visual appearance of possible outliers. For these three effect sizes (0.06, 1.40, and 1.51), while the confidence intervals may be overlapping, the weighted effect size clearly does not overlap with the majority of the effect sizes. We looked further into Turner's (2011) on the effects of a reform-based science classroom by faculty members trained in a NASA curriculum.

The results were statistically significant for the faculty members (effect size of higher education faculty were excluded from this study) of the reformed science methods courses as compared to a non-reform science methods course. However, statistical significance was not found for in-service teachers who had completed the reformed science methods course as compared to an in-service teacher who had not completed the same coursework. Turner provides qualitative evidence to attribute the lack of statistically significant difference based on the fact that teachers in the comparison group voluntarily attended reform-based workshops resulting in similar observable teaching practices. For each of the three moderators, the effects of professional development indicated a lack of statistically significant difference between groups within the moderators of teacher type, subject, and outcome measure. Given the homogeneity of the studies, this was not a surprise, however, again referring to the three studies, an interesting investigation may be to consider the duration of the studies, years of experience of in-service teachers, and the type of professional development conducted in each study.

Limitations

While the fail-safe *N* for this study was 742, it is unlikely that we might find over 700 articles to include in this meta-analysis. However, there was a larger representation of mathematics studies compared to science content areas. This study included 11 mathematics studies compared to 4 science studies. Additionally, like all meta-analyses this study was limited by the data available in primary studies. Because the unit of analysis for this study was prior studies examining reform-based professional development, our analysis and findings were limited by the quantity and quality of the available studies. Nonetheless, the data integrity of the included studies was more than adequate and representative of work in the field.

Conclusion

The results from this present study highlight the growth of pedagogical content knowledge across the included studies. Results indicate that professional development focusing on PCK yields a statistically significant mean effect size (d = 0.51, [0.43, 0.60]). Also, the homogeneity across the studies corroborates the moderate growth of PCK in math and science teachers after completing professional development incorporating PCK. Future considerations for follow-up studies may include not only duration of the study, but also number of hours within the professional development and the type of professional development. Regarding moderator effects, the lack of any statistically significant differences between groups in the various moderators (e.g. teacher type, subject, or outcome measures) also supports the moderate growth of PCK. With an increased federal focus on effective instruction, we hope these results will influence professional developers and practitioners in the field to continue to their efforts. Specifically, we hope professional developers will consider more interdisciplinary STEM professional development efforts given the lack of statistically significant difference in effects across mathematics and science content. This would help to further promote STEM education as a collaborative and interdisciplinary field.

Notes

1. SCK measures Specialized Content Knowledge whereas KCS measures Knowledge of Curriculum and Students. While KCS is technically under PCK, the items listed in the multiple-choice assessment were targeted to address the analysis of student work and misconceptions.
2. KCT is the knowledge of content and teaching and measures how the two components are integrated.
3. This article was initially included in the preliminary meta-analysis, however, after further inspection, the study did not include a form of professional development. The study compared novice teachers and experienced teachers in a school setting. Professional development or training of some sort was not a factor in this study.

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