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LEARNING OVER TIME: PEDAGOGICAL CHANGE IN TEACHING MATHEMATICAL INQUIRY

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Inquiry pedagogies are often advocated for equipping students with 21st century skills, but teaching mathematics through inquiry is difficult. A longitudinal study investigated teachers' experiences of learning to teach mathematical inquiry over time. Using the Productive Pedagogies framework, this paper reports on aspects of practice that evolved for twelve primary teachers as they gained experience with inquiry over three years.

School mathematics is criticised for emphasising closed problems with set answers (Hollingsworth, Lokan & MacCrae, 2003). Many students find mathematics boring and lacking relevance (McPhan, Morony, Pegg, Cooksey, & Lynch, 2008). Declines in students studying advanced mathematics has prompted recommendations to build capacity and interest in mathematics by improving mathematics teaching and promoting inquiry (Australian Academy of Science, 2006; Council for the Mathematical Sciences, 2004). Inquiry addresses ill-structured problems, where the problem statement, goals, or solution paths contain ambiguities that require negotiation (Reitman, 1965). Most everyday problems are ill-structured; evidence is often conflicting, requiring one to seek potential causes of the problem and generate a range of possible solutions (Walker & Leary, 2008). Through mathematical argumentation, justification, and hypothesis, mathematical inquiry generates fresh understandings, appreciation of complexities in problem contexts and new questions to explore (Magnusson & Palincsar, 2005).

A major issue in mathematics education is to find ways to support teachers to develop inquiry pedagogies in mathematics. Researchers have identified challenges that teachers face when teaching inquiry (mostly in science): envisioning inquiry processes, managing uncertainties that arise, and creating a culture of inquiry (R. Anderson, 2002; Crawford, Krajcik, & Marx, 1998). Little is known about teachers' experiences as they move from these challenges towards expertise.

A longitudinal study was designed to understand teachers' experiences as they developed proficiency teaching mathematical inquiry. This paper presents findings from analyses of classroom lessons of twelve primary teachers' over three years using the Productive Pedagogies framework (State of Queensland, 2002). Areas of their pedagogies that shifted are discussed.

Literature

Inquiry is relatively uncommon in mathematics classrooms where the focus is on problems that are well-structured—that is, problems in which there are no ambiguities (context-free), or where the problem is embedded in context but decisions have already been made to address the ambiguities. Because of this, learners and teachers in mathematics may lack confidence to contend with uncertainties that arise or manage the deliberation needed to wrestle with complexities in the problem. Initial experiences can be especially daunting, as teachers are often disappointed when lessons do not run as expected (R. Anderson, 2002; Makar, 2010). "There is a danger that … initial difficulties with implementation and disappointment with student performance can lead to a premature rejection of [these] new pedagogies" (Krajcik et al., 1998, p. 341).

In a large scale review of literature on mathematics professional development, Doerr, Goldsmith, and Lewis (2010) conclude that "repeated cycles of experimentation, reflection, and revision [are] required to change elements of instruction" (p. 4), particularly in areas such as inquiry which are strongly connected to teachers' beliefs. They suggest that key features of professional development that do make a difference—substantial time investment, systemic support, and opportunities for active learning—are rare in programs involving more than a few teachers. In evaluating sustained professional development projects, Heck, Banilower, Weiss, and Rosenberg (2008) report that teachers' use of innovation was greatest in the first 80 hours of interaction and then leveled off, but after 160 hours, innovation increased again. This suggests that innovation is sustained in the long term, but only if teachers are supported over time, remembering that change is non-linear and idiosyncratic (Clarke & Hollingsworth, 2002; S. Anderson, 2010).

The Productive Pedagogies framework

In order to understand teachers' changing experiences of teaching inquiry, there is a need to document classroom observations of inquiry practices both within a single classroom over multiple years and collectively as teachers gain experience. Finding a framework without shortcomings was unlikely, particularly since characteristics that make up quality classroom pedagogies are contested. Productive Pedagogies was developed for the Queensland School Reform Longitudinal Study (QSRLS, 2001a) as a way to observe and document pedagogical practices across Queensland.

Table 1. Productive Pedagogies (QSRLS, 2001a).

Intellectual Quality Knowledge presented as problematic Higher order thinking Depth of knowledge Depth of understanding Substantive conversation Meta-language	*Supportive Classroom Environment* Students' direction of activities Social support for student achievement Academic engagement Explicit quality performance criteria Student self regulation Narrative
Connectedness School subject knowledge is integrated Link to background knowledge Connectedness to world beyond classroom Problem-based curriculum	*Recognition of Difference* Knowledge explicitly values all cultures Representation of non-dominant groups Group identities in a learning community Active citizenship

The opportunities provided by the Productive Pedagogies seemed positive in their emphasis on many of the same qualities valued in inquiry. Productive Pedagogies consists of 20 pedagogical practices organised into four main clusters: Intellectual Quality, Connectedness, Social Support and Recognition of Difference (Table 1). Although they have been critiqued even by their authors (e.g., Ladwig, 2007), the framework has been used extensively. Researchers have refined and updated the framework (Mills & Goos, 2007), but it has remained substantially unchanged since its publication in 2001.

Method

The research question was, “Which aspects of teachers’ practice change as they gain experience in teaching mathematical inquiry?” The data reported in this paper come from teachers who completed at least three years in an ongoing longitudinal design-based research study. In design-based research, the researcher focuses on simultaneously studying and improving the research context through a number of reflective and retrospective cycles. The benefit of design-based research is that

> … in contrast to most research methodologies, the theoretical products of design experiments have the potential for rapid pay-off because they are filtered in advance for instrumental effect. They also speak directly to the types of problems that practitioners address in the course of their work. (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003, p. 11)

Figure 1 represents the model used in the project to understand teachers’ changing experiences as articulated by the teachers in the study (Makar, 2008).

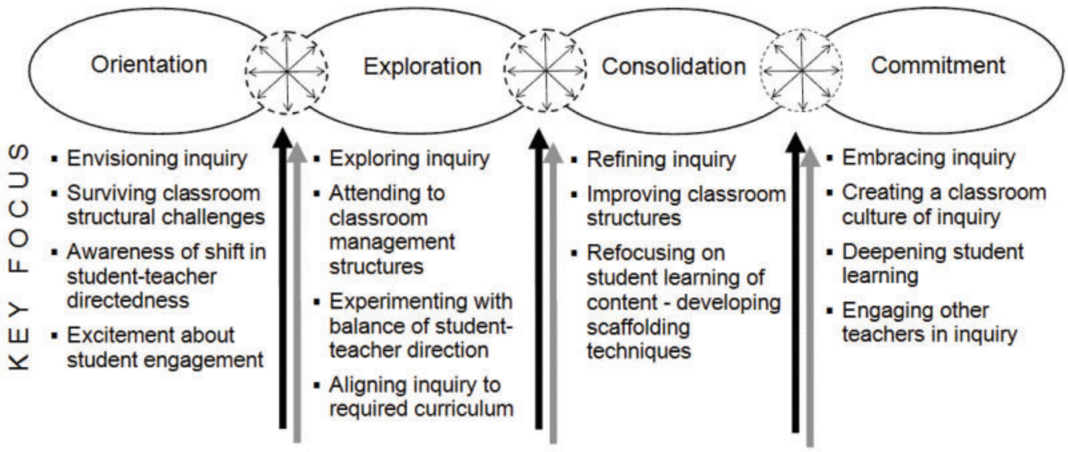


Figure 1. *Model of teachers’ changing experiences in learning to teach mathematics through inquiry.*

The first phase (2006–2007) included five teachers from a large primary school in a middle class suburb. The next phase (2007–2009) expanded to twenty teachers—six from the original school and fourteen teachers (the entire school) from a rural school—in a low socio-economic area in the same region. As is common in longitudinal research, the project experienced attrition due to transfer. Data were collected from 23 teachers, with new teachers recruited as teachers left. This paper limits its focus to the 12 teachers in the study for at least three years. Five teachers (all female) were from the suburban school and seven (six female, one male) from the rural school.

Teachers participated in three to four days of professional development per year and taught a mathematical inquiry unit each term (a term lasts 10 weeks). Professional development seminars gave teachers time to collectively reflect, share experiences and obtain peer feedback. During the seminars, teachers also engaged in learning experiences that highlighted particular aspects of inquiry (e.g., ill-structured problems, assessment, emphasising concepts), built understandings of inquiry processes (e.g., working with ambiguity, understanding the role of evidence) and developed a learners' perspective of inquiry (e.g., experiencing frustration, breakthroughs, cognitive drivers).

The teachers developed their own units or modified published units; a unit lasted anywhere from two lessons to several weeks. During or after lessons, the researcher and teacher engaged in informal conversation to offer individualised support, query experiences, validate uncertainties and offer advice if requested. Advice was used sparingly to understand teachers' experiences with limited support (the current phase includes more explicit and systematic feedback and targeted skills in teaching inquiry).

Data collection and analysis

Classroom lessons were videotaped; it was not possible to videotape every lesson, but in most cases at least two lessons from every teacher were taped each term. Five hundred and sixty-five lessons were videotaped in the first two phases (2006–2009). This paper presents analyses of these videos, limited to teachers in the project for at least three years. To gauge teachers' pedagogies over time, a stratified random sample of lessons was selected to analyse, with lessons from each teacher randomly sampled according to the criteria in Table 2 to align with the model used in the project (Figure 1).

Table 2. Categories of lessons in the sample coded.

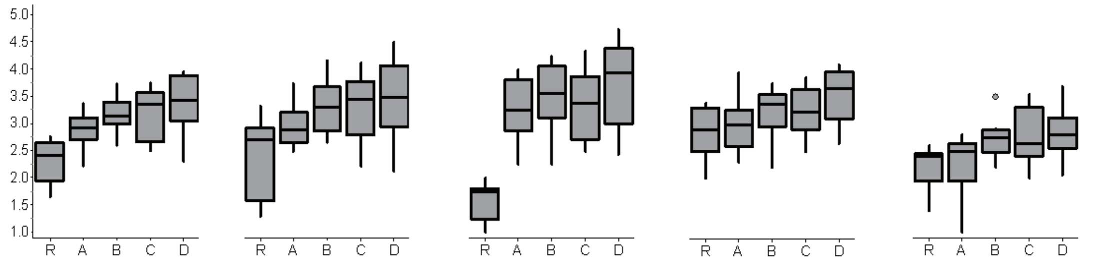
Category	Cumulative terms teaching inquiry	Random sample of lessons coded
R	Regular (non-inquiry) maths lesson (any term)	1 per teacher
A	First Inquiry (term 1 of their participation)	2 per teacher
B	Remainder of first year (terms 2-4)	2 per teacher
C	Second year (terms 5 – 8)	2 per teacher
D	Third year (terms 9 – 12)	2 per teacher

Lessons were identified by a code to mask their category and analysed with the Productive Pedagogies Classroom Observation Scheme (Queensland School Reform Longitudinal Study [QSRLS], 2001b). The Scheme describes qualities of practice in each Productive Pedagogy on a scale of 1 to 5 (with 5 high). A team of researchers led by the author scored the sample after a period of moderation (and interim cross checks). One hundred and one lessons were analysed in all (in a few cases, only one taped lesson was available), with scores averaged across teachers' two lessons.

Teachers were also assigned a difference score for each Productive Pedagogy and pedagogy cluster based on shifts during the first year (AB, the difference in their average A score and average B score), the first three years (AD) and comparisons between initial inquiry lessons and non-inquiry lesson (RA). Distributions of RA, AB and AD were tested with a two-tailed test of a single mean (e.g., H_a: RA≠0).

Results

Figure 2 provides a snapshot of the distributions of the twelve teachers' scores overall (average across Productive Pedagogies) and for each pedagogy cluster in the five categories—R (regular lesson), A (first inquiry), B (first year), C (second year) and D (third year). The graphs suggest that the teachers' pedagogical practice generally improved over time. Some patterns are more complex, however, than the graphs reveal.



Overall	Intellectual Quality	Connectedness	Supportive Environment	Recognition of Difference
R: 2.3 (0.42)	R: 2.4 (0.73)	R: 1.6 (0.37)	R: 2.9 (0.49)	R: 2.2 (0.37)
A: 2.9 (0.37)	A: 3.0 (0.42)	A: 3.3 (0.57)	A: 3.0 (0.47)	A: 2.3 (0.57)
B: 3.2 (0.32)	B: 3.3 (0.47)	B: 3.5 (0.64)	B: 3.2 (0.51)	B: 2.7 (0.35)
C: 3.2 (0.49)	C: 3.3 (0.61)	C: 3.3 (0.63)	C: 3.3 (0.44)	C: 2.8 (0.52)
D: 3.4 (0.55)	D: 3.4 (0.73)	D: 3.7 (0.84)	D: 3.5 (0.53)	D: 2.9 (0.49)

Figure 2. Distributions of scores in each pedagogy cluster and overall for a regular lesson (R), first inquiry (A) and in inquiries in the first (B), second (C) and third years (D). The table shows means (sd) of each pedagogical cluster in each category of inquiry experience (R, A, B, C, D).

Such broad comparisons offer only a vague impression of the teachers' changes in pedagogical practices in their first three years. Of interest was whether patterns emerged within Productive Pedagogies over time. For example, did different pedagogical practices evolve at different times? Table 3 details breakdowns of change scores (RA, AB, AD) for each Productive Pedagogy and pedagogy clusters, discussed below.

Intellectual quality

Although it had a plateau in the second year, Intellectual Quality improved by about one point on average on the five point Observation Scheme from the regular maths lesson to the third year of inquiry. Three Productive Pedagogies showed significant improvement from the regular maths lesson to the first inquiry lesson (RA), particularly *Problematic Knowledge* and *Higher Order Thinking*. *Metalanguage* improved gradually but was consistently higher (low standard deviation) by the teachers' third year. *Substantive Conversation* and *Depth of Understanding* appeared difficult areas to change.

Connectedness

Connectedness was the lowest cluster in the regular maths lessons ($\bar{x} = 1.6$) yet increased to the highest ($\bar{x} = 3.7$) by the third year. The improvement from a regular maths lesson to the inquiry lessons in all pedagogies in this cluster was significantly higher almost immediately. *Knowledge Integration* and *Problem-based Curriculum* increased quickly then plateaued or slightly declined. *Link to Background Knowledge* and *Connectedness to the World* increased slowly, ending strong by year three.

*Table 3. Productive Pedagogies - shifts over the first three years. Mean (sd), p-value by category, * p<0.05, **p < 0.01.*

Productive Pedagogies	**RA (Regular lesson to first inquiry)**	**AB (across first year)**	**AD (across first three years)**
Overall	**0.56 (0.43), p = 0.00088****	**0.30 (0.37), p = 0.016***	**0.50 (0.47), p = 0.0035****
Intellectual Quality	**0.62 (0.74), p = 0.015***	0.31 (0.57), p = 0.085	0.44 (0.80), p = 0.085
• Knowledge presented as problematic	**0.77 (0.85), p = 0.0093****	0.47 (1.29), p = 0.24	0.69 (1.29), p = 0.092
• Higher order thinking	**0.88 (0.84), p = 0.0040****	0.24 (0.55), p = 0.16	0.40 (0.73), p = 0.089
• Depth of knowledge	**0.71 (0.80), p = 0.011***	0.39 (0.85), p = 0.14	0.46 (1.03), p = 0.15
• Depth of understanding	0.17 (1.09), p = 0.61	0.15 (0.88), p = 0.58	0.35 (0.93), p = 0.21
• Substantive conversation	0.81 (1.44), p = 0.077	0.22 (1.05), p = 0.48	0.35 (1.28), p = 0.36
• Metalanguage	0.38 (0.93), p = 0.19	0.41 (0.93), p = 0.15	**0.38 (0.58), p = 0.046***
Connectedness	**1.69 (0.63), p < 0.0001****	0.21 (0.59), p = 0.23	0.42 (0.77), p = 0.085
• School subject knowledge is integrated	**2.0 (1.04), p < 0.0001****	-0.10 (1.09), p = 0.75	-0.35 (1.83), p = 0.52
• Link to background knowledge	**0.85 (1.04), p = 0.016***	0.60 (1.05), p = 0.074	**0.77 (0.92), p = 0.014***
• Connectedness to world beyond classroom	**0.96 (1.01), p = 0.0073****	0.42 (0.97), p = 0.16	**1.17 (1.23), p = 0.0071****
• Problem-based curriculum	**2.96 (1.08), p < 0.0001****	-0.063 (0.69), p = 0.76	0.10 (0.69), p = 0.61
Supportive Classroom Environment	0.12 (0.39), p = 0.32	0.22 (0.41), p = 0.09	**0.54 (0.40), p = 0.00074**
• Students' direction of activities	0.67 (1.40), p = 0.13	0.34 (1.34), p = 0.40	0.75 (1.23), p = 0.058
• Social support for student achievement	-0.15 (0.89), p = 0.58	0.25 (0.91), p = 0.36	**0.69 (0.85), p = 0.018***
• Academic engagement	**0.56 (0.89), p = 0.050***	-0.22 (0.92), p = 0.43	0.13 (0.92), p = 0.65
• Explicit quality performance criteria	0.06 (1.09), p = 0.85	0.29 (0.73), p = 0.19	**0.63 (0.99), p = 0.050***
• Student self regulation	-0.56 (1.17), p = 0.12	0.42 (1.17), p = 0.24	0.5 (1.01), p = 0.11
• Narrative	0.58 (1.16), p = 0.11	**0.88 (0.88), p = 0.0054****	0.67 (1.32), p = 0.11
Recognition of Difference	0.02 (0.55), p = 0.90	0.46 (0.72), p = 0.052	**0.60 (0.59), p = 0.0044****
• Knowledge explicitly values all cultures	**0.75 (0.54), p = 0.00057****	-0.10, (0.81), p = 0.69	-0.46 (0.81), p = 076
• Representation of non-dominant groups	0.04 (1.33), p = 0.92	0.57 (1.27), p = 0.15	0.50 (1.33), p = 0.22
• Group identities in a learning community	-0.13 (0.93), p = 0.65	0.38 (1.38), p = 0.36	**0.63 (0.77), p = 0.017***
• Active citizenship	**-1.15 (0.46), p < 0.0001****	**0.55 (0.59), p = 0.0089****	**1.69 (0.86), p < 0.0001****

Supportive classroom environment

Teachers noticed at once that students were engaged in inquiry lessons (similar reports are made by Kennedy, 2005), an observation supported by the data (t_{11}=2.2, p=0.050). Some areas declined initially; this was most evident in *Student Self-Regulation*, related to classroom management, where teachers may have felt uncomfortable with less control and higher noise levels. *Student Self-Regulation* was generally high in regular lessons ($\bar{x}$ = 3.9, s=0.43) and never reached this level in inquiry. These pedagogies typically took longer to improve, with only two significantly higher by year three (*Explicit Quality Criteria*, *Social Support for Achievement*). This suggests that developing a classroom culture of inquiry may be one of the most challenging aspects of teaching mathematical inquiry.

Recognition of difference

This category did not demonstrate strong growth in teachers' first year of teaching inquiry, particularly *Active Citizenship* which dropped dramatically. This may be a reflection of teachers' initial classroom management concerns (Makar, 2010). *Active Citizenship* improved substantially by year three, ending strong ($\bar{x}$ =3.5, s=0.75).

Discussion

This paper examined evidence of teachers' pedagogical shifts over time as they gained experience in teaching mathematics through inquiry with support. In regular mathematics lessons, every pedagogical cluster scored on average below mid-level (score of 3 on a scale of 1 to 5) and most ended well above mid-level by the third year of inquiry teaching (Figure 2). In some pedagogies, such as *Connectedness to the World*, the average for the regular mathematics lessons was disappointingly low ($\bar{x}$ =1.3). This may say as much about many regular maths lessons as it does about inquiry. If students are not made aware of the way that mathematics is used in the world, it is of no surprise that many students believe mathematics lacks relevance and choose to discontinue studying it (Australian Academy of Science, 2006; McPhan et al., 2008).

Many pedagogies improved in the first year, declined slightly in the second year, and improved again in the third year. This pattern suggests the importance of supporting teachers in the first year (Makar, 2010), throughout the second and into at least the third year where they are gaining confidence. Innovative pedagogies place significant demands on teachers, and targeted, timely support appears to be vital. Recognising that the primary goal of professional development is the *long term improvement of student learning*, Doerr et al. (2010) counsel that professional development must likewise focus on *sustained, long term change of teacher practice*. In particular, their review of the literature suggests that (1) extended time investment, (2) sustained support and (3) repeated opportunities for teacher learning over time are required if there is an expectation for teachers to demonstrate shifts in practice.

It is well established in the literature on teacher education that pedagogical change is difficult. The research reported here provides preliminary insights into the potential for teachers' pedagogical change when these three features—extended time investment by teachers and a teacher educator, sustained support and repeated learning opportunities—

are in place. The teachers in this study committed substantial amounts of time and energy in developing, teaching and reflecting on mathematical inquiry units for their students, the researcher invested hundreds of hours in classrooms observing individual teachers' lessons, and three to four days per year of professional development provided multiple opportunities for learning and reflection. Such a commitment from all parties questions whether this type of research can be scaled up. The next phase of the study (2009-2012) with over 40 teachers is currently underway, focusing on investigating and building foundations for a scalable model.

Practical implications

Teachers as well as those involved in teacher education and professional development must understand the nature of challenges and shifts associated with mathematical inquiry. For teachers, acknowledging that learning to teach mathematics through inquiry takes time can assist them in persisting through periods of frustration. Having a better understanding of the difficulties of learning to teach mathematics through inquiry may assist teacher educators in better supporting and validating teachers' experiences with inquiry pedagogies. The study reported in this paper suggests several practical implications for teachers, schools and teacher educators, including areas of greatest challenge, improved awareness and attention to the "implementation dip" of new pedagogical practices and the value of longitudinal professional development.

Patterns of pedagogical change and the "implementation dip"

Although the combined average of teachers' overall productive pedagogy score tended to rise as they gained experience (Figure 2), the changes did not happen in a linear, predictable fashion. In some areas, the improved practice was evident almost immediately. Even among those areas which improved in the first inquiry unit, the progression of pedagogical change in the following again was unpredictable. The pedagogical clusters of *Supportive Classroom Environment* and *Recognition of Difference* eventually rose significantly above that of a traditional mathematics lesson, but this took substantially more time.

Teacher educators, principals and policymakers need to expect rather than eschew the non-linear nature of teachers' adoption and adaptation of new pedagogical practices. This study is a reminder that new practices not only take time, but improvement pathways shift and turn in unexpected ways. For example in this study, dips and plateaus were evident in pedagogies from every pedagogical cluster. Although implementation dips have been reported in the literature (see for example, work by Fullan (2007) and Pendergast (2005) on implementing whole school pedagogical innovation), they are typically met with surprise and disappointment. In some cases, a judgement is made hastily that the dip indicates the new pedagogical practice has gone into disuse. Instead, implementation dips need to be acknowledged as a normal part of the process so that teachers are supported and encouraged to persist through them rather than left feeling guilty.

Sustained professional development

The data suggest that the teachers' overall pedagogical practices in the study improved within the first year of their engagement with inquiry (agreeing with research by Heck et al., 2008). It is important to note, however, that *sustained* engagement with professional development was likely needed beyond this first year to maintain and further improve practices. The plateau or "implementation dip" that appeared for many of the teachers after the first year strongly suggests the importance of this ongoing support through this period when teachers' initial engagement with inquiry may be starting to wane. The pressures of "performativity" (Ball, 2003) may have also amplified the dip as inquiry is sometimes considered to be at odds with accountability.

The design of this study ensured that the teachers received regular classroom support and professional development throughout the study. While it points to some positive outcomes of school-university partnerships, there are questions about whether this type of professional development can be applied more broadly. This and several other questions are raised by this study requiring further investigation.

- What models of "scaling up" improve inquiry-based pedagogies in mathematics more broadly (e.g., peer coaching, whole school adoption)?
- What supports can target an "implementation dip" to lessen its impact or duration?
- How can more long-term classroom-based professional development be encouraged? What aspects (e.g., classroom feedback, reflection, collaboration) are most critical?
- What other frameworks are effective for evaluating and self-assessing inquiry-based teaching practices in mathematics?
- How do teachers' experiences with inquiry-based teaching affect their teaching of regular maths lessons?

This study has implications as well for both teachers and teacher educators about the pedagogies of regular mathematics lessons. In particular, the pedagogy of *Connectedness with the World* was unexpectedly low. School mathematics is often poor at being explicit about connections between content being taught and the world beyond school walls. This study is a reminder of the importance in regular mathematics lessons of making the relevance and interconnectedness of mathematics explicit.

Conclusion

The findings of the longitudinal study previously published had been based on teachers' self-reports of challenges and opportunities in teaching inquiry (Makar, 2007, 2010) and case studies of exemplars of teaching and learning (Allmond & Makar, 2010; Makar & McPhee, 2009; Fielding-Wells, 2010). This paper extends the evidence base of this longitudinal study by presenting analyses of quantitative data from repeated observations of teachers' classroom practices over three years. As a body of work, the interweaving of multiple research approaches strengthens the overall message that implementing mathematical inquiry, while highly promising as a pedagogical practice, is challenging for teachers and requires substantial time and resources to operationalise.

In this study the changes to teachers' pedagogies were non-linear and did not follow a predictable curve. This is a timely reminder that facilitating teacher change is complex, even when teacher development strategies tick all of the "effective professional development boxes". Perhaps this is because innovation is not a process of adoption, but rather a process of implementation involving progress and outcomes that are, necessarily, highly reliant on interaction with the particularities of the local context (S. Anderson, 2010).

Acknowledgements

This research was funded by The University of Queensland (ECR Grant, 2006-07) and the Australian Research Council (LP0776703, 2007-09) in partnership with Education Queensland. The author would like to thank the teachers for their generous contributions to the research, Sue Allmond, Kym Fry, Lisa Lim and Jill Wells who assisted with the data collection and video analysis, and Robyn Gillies, Mia O'Brien and Jill Wells for their feedback on earlier versions of the paper.

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