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ORIGINAL ARTICLE

Emergent pedagogies and the changing role of the teacher in the TI-Nspire Navigator-networked mathematics classroom

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Abstract It is generally accepted that the introduction of networked technologies to the mathematics classroom can stimulate an irreversible change within the classroom concerning: the role of the teacher; the nature of the classroom tasks; and the way in which students engage in the process of learning mathematics. This article will use the context of a classroom-based study into teachers' developing practices with the TI-Nspire Navigator-networked system of handhelds to explore the nature of these practices and the implications for the mathematics classroom. The emergence of a range of formative assessment practices is described and the implication of these practices on desirable learning opportunities (as described by the teachers themselves) is discussed.

Keywords Networked handheld technology · Teacher development · Formative assessment · Mathematics

1 Introduction

There is a well-established body of research that has focused on the introduction of handheld technologies alone, which include basic, scientific and graphing calculators, to the school mathematics classroom, a claim for which the existence of this special edition of ZDM provides strong evidence. Within existing research, much emphasis has been placed on the impact of handheld technologies on the students' experiences. Theories have emerged concerning the process of integration of the technology as a learning tool, the ways in which students' mathematical thinking changes and comparisons of the with-technology versus without-technology learning outcomes, which will be expanded upon in the next section (Blume and Heid 2008; Hoyles and Lagrange 2009; Hoyles et al. 2004).

Previous research into students' uses of handheld technology has suggested important aspects of the teachers' role in mediating students' actions in mathematics lessons: for example, the importance of the teacher's role in drawing students' attentions to the connecting mathematical ideas within a web of knowledge and in shaping the relationship between computational media and mathematical knowledge (Guin and Trouche 1999).

However, a crucial factor in the adoption of technology in mathematics classroom concerns the perceptions, attitudes, professional development experiences and support networks for teachers to enable them to integrate its use into their regular practice; so, the research lens has moved to focus on teachers (Artigue 1998; Hoyles and Lagrange 2009; Ruthven 2008). This article will begin by briefly summarizing some of the research outcomes of relevant studies and proceed to report on a recent project, which sought to elicit the emerging practices of a group of seven mathematics teachers as they began to use a networked handheld system, *TI-Nspire Navigator* (Texas Instruments 2009), with learners in their classroom setting. It will describe the key features of the networked handheld system and the results of the study. The article will conclude by summarizing the findings of this study and outlining some areas for further research. Whilst extending the discussion to connected classroom systems in general seems promising, the choice has been to restrict the discussion to handheld technologies and to keep a further discussion for future research.

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2 Researching teachers developing their classroom use of handheld technologies and networked handheld technologies: what do we know?

A number of studies have focused on teachers as they began to use handheld technology in the mathematics classroom and have sought to develop an understanding of the process through which this happens. Such studies have revealed a number of important considerations:

- The process of finding legitimate uses for handheld technology and integrating it to become an essential constituent in the meaning of mathematical tasks is a slow and complex one for teachers (Artigue 1998, 2002; Laborde 2001).
- Surveys of school use of graphing calculators reveal a low proportion of teachers with a fluent grasp of its functionality to enable its use as a conceptual tool for teaching and learning mathematics (Rodd and Monaghan 2002).
- The introduction prompts a fundamental rethinking of the role of the teacher in the classroom (Clark-Wilson 2008; Guin and Trouche 2002).
- Teachers whose underlying beliefs about mathematics did not view the subject *only* as a set of rules and algorithms for students to learn were more likely to focus on their students' cognitive and conceptual responses when working with graphing calculators (Burrill 2002).
- The role, knowledge and beliefs of the teacher influence the emergence of rich usage of the graphing calculator to include: encouraging interpretation and explanation; a transition to more interpretive tasks over computational tasks; the valuing of algebraic arguments to support graphically and numerically generated conjectures; and to a devaluing of the calculator as an authority in a mathematical argument (Doerr and Zangor 2000).

However, a perceived limitation in the use of handheld technology in classrooms concerns the way in which its use as a private device conflicts with the desire for a more collaborative learning environment in which students' task outcomes and strategies are shared (see for example, Doerr and Zangor 2000). Consequently, technology has been evolving to enable such collaborations to be possible through a wireless classroom-based network system, such as the system developed for the TI-Nspire handheld, *TI-Nspire Navigator* (Texas Instruments 2009).

At the time of writing, much of the research concerning the wirelessly networked handheld classroom has been speculative in its nature (Center for Technology in Learning 2008; Roschelle and Pea 2002), awaiting developments in the hardware to realize the potential of a truly flexible classroom system.

Dougherty's pilot study, which involved the TI-Navigator system with TI-84 graphing calculators in one classroom in Hawaii, concluded,

> The use of TI-Navigator technology supports the development of a collaborative classroom environment by enhancing student interactions, focusing students' attention on multiple responses, and providing opportunities for students to peer- and self-assess student work. The ability to display a full class set of data or task responses supports a problem-solving approach to developing skills and concepts. (Dougherty 2005, p. 28).

These themes also featured in the reported outcomes of the French TI-Navigator with TI-84 research study (Hivon, Pean, and Trouche 2008) which also suggested that the TI-Navigator had changed the nature of the mathematics classroom environment by:

- offering an opportunity to change the nature of classroom mathematics tasks;
- offering new opportunities for both cooperative and collaborative group learning;
- increasing the complexity of the teacher's role with respect to 'orchestrating' the lesson.

The case study described by Penuel (2008), which used the SimCalc application for the TI-84 with the TI-Navigator system, also highlighted the importance of paying 'considerable attention to what kind of *tasks* are important to assign students such that the important mathematics is revealed'. Penuel also highlights the importance of the teacher's underlying pedagogical approach, saying 'the power of Alex's pedagogy rests on his ability to exploit connectivity to make visible fundamental concepts of algebra, especially with respect to developing a functional understanding of algebra'.

A comparative research study carried out in Canada (Sinclair 2008), which aimed to contrast aspects of TI-Navigator with TI-84 use in three schools reported on the implications of this use on the development of teachers' pedagogical approaches. This study involved 'typical' teachers over the period of a school year and, writing about this progression, the researchers concluded:

> They were using student responses as cues for making decisions about the direction of subsequent work, had students working together in pairs or groups, and were beginning to engage students in analysis of errors. We also noticed an increased effort on the part of all four teachers to involve the students in mathematical investigations. (Sinclair 2008, p. 24)

Sinclair's study also sought to contrast the nature of the mathematical discussions in the experimental (with TI-Navigator) and control classrooms. The study reported,

> It would seem that in the process of learning the discourse of mathematics, students would benefit from contributing to and talking about shared objects (whether concrete or virtual). Certainly, our observations provide some evidence that, especially in the two classes observed at School B, classroom conversation had started to develop around TI-Navigator displays. Although full discussions were not held, there was a sense in which students were actively and collectively involved in the task at hand. (Sinclair 2008, p. 28)

Whilst also recognizing the imbalance between the classroom discussions that the researchers observed, they also concluded that the use of TI-Navigator supported the development of richer classroom discourse.

3 Design of the study

3.1 Research aims and methodology

This exploratory study aimed to research the emergent practices of classroom teachers as they began to use a wirelessly networked handheld system in their classrooms. In particular, it aimed to find out more about:

- the aspects of the teachers' classroom use of the TI-Nspire Navigator that promoted 'desirable' classroom pedagogies;
- the nature of the tasks or mathematical starting points that led to 'enhanced' student engagement and achievement in mathematics.

It was assumed that the teachers would want to develop tasks and teaching approaches, which would use the various features and functions of the systems in ways that represented improvements on their previous practices. Consequently, the teachers' individual interpretations of the words 'desirable' and 'enhanced' were of great importance to the research approach as, in both cases, the nature of the data that the teachers provided would reveal rich evidence about their views, practices and perceptions of mathematics as a subject, and its associated pedagogies.

The study adopted a grounded research methodology in which the teachers used a systematic approach to evaluate their own classroom practices supported by: a common lesson evaluation form (see Appendix 1); supportive lesson observations; and ongoing support by e-mail, phone and face-to-face meetings. In addition, semi-structured teacher and student interviews were also carried out. The focus of the pilot study was limited to the following TI-Nspire Navigator functionalities: *Screen Capture*; *Quick Poll*; *Live Presenter*; *File management* and *Class Analysis*, each of which will be briefly described later in the article.

3.2 Selection of schools and teachers

This TI-Nspire Navigator pilot followed on directly from the TI-Nspire pilot carried out in seven English secondary schools during 2007–2008 and reported in Clark-Wilson (2008). Two of the teachers (from England) and one of the project mentors (from Scotland) were invited to trial the TI-Nspire Navigator system in their classrooms. Two teachers from Sweden and two teachers from the Netherlands were also invited to take part in the pilot study as they had experience of using TI-Nspire handhelds and software in their classrooms. These teachers were chosen partly because they had a good command of the English language and would be able to actively engage with the project team, but more importantly to increase the size of the sample. As such all of the teachers represented an opportunistic sample. The teachers selected pilot classes, which ranged in age from 12 to 17 years. The study was not designed to be comparative with respect to either the cultural differences between the classroom settings or the quantitative analysis of student attainment data. The study took place between April 2009 and July 2009.

3.3 Organizing the students' access to TI-Nspire Navigator

Each of the seven pilot teachers made their own decisions about the way in which their students would access TI-Nspire Navigator. In the Swedish and Dutch schools, all of the students owned a TI-Nspire handheld, or had been loaned one by the school. In the English school, the students were loaned a TI-Nspire handheld for each lesson and in the Scottish school two classes were involved in the pilot study. In one class, the students were loaned their own TI-Nspire handheld and in the other they were provided on a lesson-by lesson basis. Consequently, the students' familiarity with TI-Nspire technology varied between 0 and 21 months, although software and hardware upgrades had resulted in a number of significant changes during this time.

3.4 Data collection

A wide range of sources of data was submitted by the teachers, which included the following:

- Written lesson evaluations for all of the lessons they had taught with the system, the main emphasis of which

was to support the teachers to articulate the story of the lesson, particularly concerning the planned and incidental uses of the TI-Nspire Navigator system (see Appendix 1).
- An outline lesson structure or plan.
- A compilation of the paper and electronic resources used to teach the lesson. These included: the teacher's own notes; students' and/or teachers' TI-Nspire files; task or resource sheets for students; and other practical mathematics resources.
- Students' TI-Nspire files collected at the end of lesson sequences.

This data were supplemented by: lesson observation data; teacher interviews and questionnaires; student interview data; teachers' lesson logs; and e-mail correspondences. It was then coded according to the teacher, lesson number and source type and input into Nvivo8 software (QSR International 2008) to facilitate the process of analysis.

3.5 The process of data analysis

As previously stated, the study adopted a grounded theory methodology (Glaser and Strauss 1967) for the following reasons. As the main source of data for the project was the teachers' own words and descriptions of their uses of the TI-Nspire Navigator system, it was obvious that to make sense of this, an analysis of their texts would be necessary. Secondly, as a new piece of technology, the research base for TI-Nspire Navigator is under-developed. Consequently, a grounded theory approach would enable the categories of use and rationales to support these categories to emerge from the data and lead to the development of new theories on the teachers' classroom practices.

The process of data analysis was carried out by the main researcher and involved the research data being input into Nvivo8. The data analysis was carried out in two phases. During the first phase, the lesson evidence was scrutinized and the use of each of the TI-Nspire Navigator features was analysed quantitatively, with each use being counted only once within a single lesson if it occurred. The second phase of data analysis involved a scrutiny of the lesson data, looking for evidence of the teachers' descriptions of the 'desirable' features and 'enhanced' student engagement and achievement. This led to a set of data codes (see Appendix 2), which were grouped and refined to produce the themes about which the research findings are organized. In all cases, the teachers' descriptions were supported by actual classroom examples.

3.6 The approach to professional development

Establishing the sense of community for this project was seen as an essential foundation on which we could build the participating teachers' sense of being both supported and valued. It was deemed important that the project maintained a clear sense of "researching with", which had come about by the privileging of the teachers' classroom stories. The teachers had an opportunity to meet each other and share their initial experiences with TI-Nspire Navigator.

This was achieved through two 1-day meetings during which they: presented examples of the lessons they had taught; discussed their in-depth lesson evaluations; looked at students' work; shared some of the emerging issues and worked on possible solutions.

4 The TI-Nspire Navigator classroom system: a brief overview

What follows is a brief description of the technical functionality of the TI-Nspire Navigator classroom system that the teachers used to provide the contextual background for the project. The implications of the various functionalities, and the uses that the teachers developed for them, are described more fully in the research findings. The system adopted by the study used the TI-Nspire (non-CAS) handheld, which integrates a set of calculator, spreadsheet, dynamic geometry, graphing and notes applications (Fig. 1).

4.1 The classroom setup

In all of the pilot classrooms, the teachers used TI-Nspire handhelds with TI-Nspire Navigator wireless cradles in normal classrooms and the teachers' computer connected

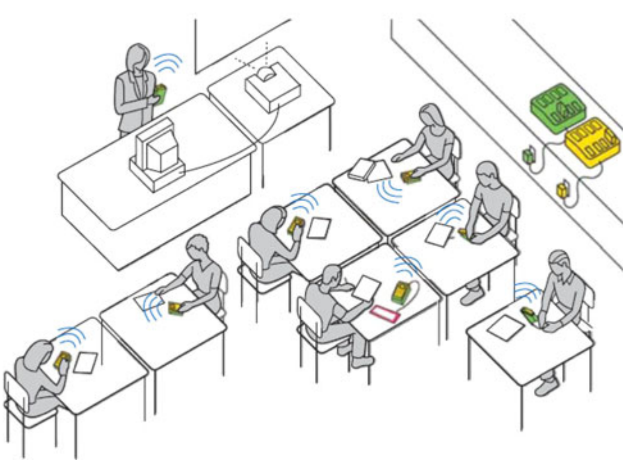

Fig. 1 The TI-Nspire Navigator classroom setup

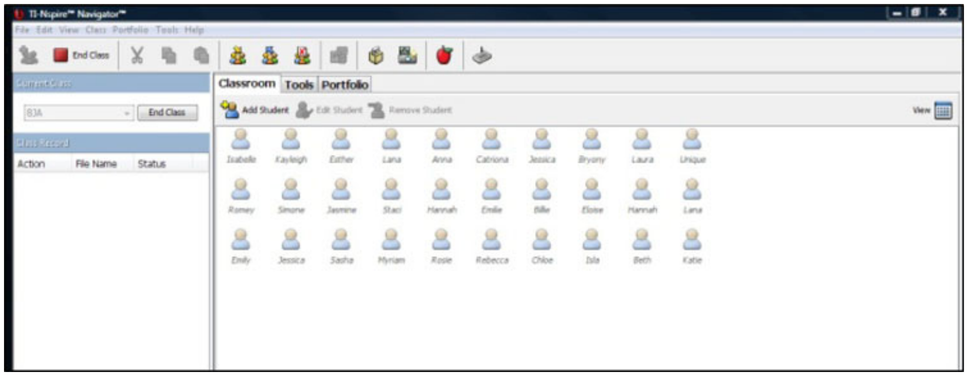

Fig. 2 TI-Nspire Navigator software

to a data projector. Some classrooms were also resourced with an interactive whiteboard. Teachers had installed the TI Network Manager software and set up the classroom network through the Access Point to the teacher's computer.

4.2 Overview of TI-Nspire Navigator software

The TI-Nspire Navigator software provided the organizational platform for the lessons. Student names had been entered (or imported) in advance of the lessons to create the 'class' (Fig. 2). This facilitated the distribution and collection of TI-Nspire files from the teacher's computer to the handhelds and provided the organizational starting point for *Screen Capture*, *Quick Poll*, *Live Presenter* and *Class Analysis*. It was also possible for teachers to be part of the class by connecting their own handheld and designating themselves as the teacher.

4.3 Distributing and collecting files

Once the class had been started and the students had logged into the system from their handhelds, it was possible for the teacher to send a TI-Nspire file to the students' handhelds as a whole class or individually, as required. These can be collected back from the students in the same way. The TI-Nspire Navigator software also facilitates the redistribution of TI-Nspire files to students, for example, at the beginning of the follow-up lesson. This is a particularly useful functionality where the teacher has reviewed and commented upon the students' work within the TI-Nspire file or the students do not own their own TI-Nspire handheld. It does not matter which handheld they choose, as their work is retained within the class portfolio rather than on any individual handheld.

4.4 Screen Capture

Once the class had been started and the students had logged into the system from their handhelds, it was possible for the teacher to show all of the students' the current handheld screens using *Screen Capture*. A variety of display formats are possible and the screens can be repositioned by dragging and dropping. The screen is automatically refreshed according to preset time values and the individual students' screens can be saved (Fig. 3).

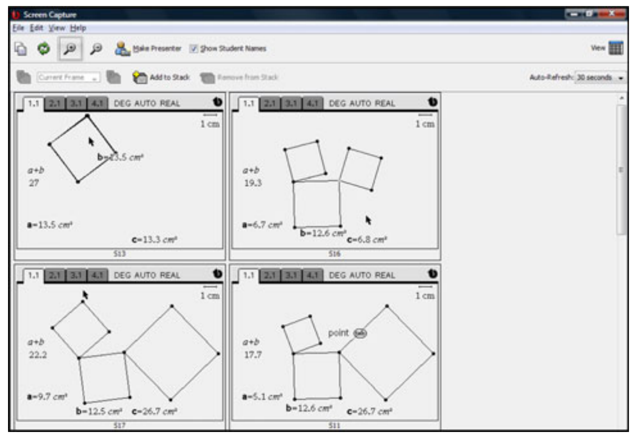

Fig. 3 *Screen Capture*

4.5 Live Presenter

From the *Screen Capture* view previously described, it is possible to select one of the handheld screens and make the owner of it the *Live Presenter*. The user's key presses and screen action is then broadcast to the whole class. It is possible to show the key press history and record the screen action as a video file (Fig. 4).

4.6 Quick Poll

The *Quick Poll* facility enables the teacher to send an immediate poll to the students, which interrupts their activity on their handheld with a pop-up question. The questions can be structured to be open response, agree/disagree, yes/no, right/wrong, true/false, always/sometimes/never and multiple choice.

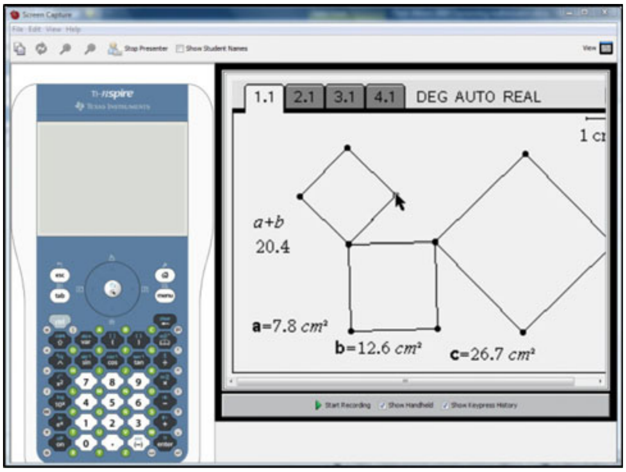

Fig. 4 *Live Presenter*

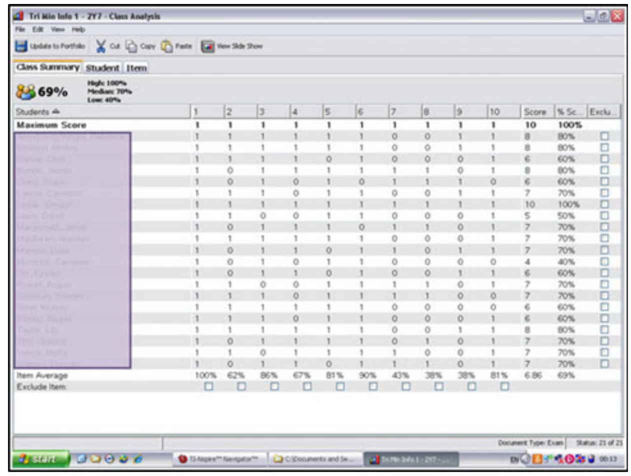

Fig. 5 *Class Analysis* view

The poll can be started, paused and stopped by the teacher and, once stopped, the results displayed with and without the students' names. A number of analysis features enable the results to be explored by common answers, a graphical display and individual students' answers.

4.7 Class Analysis

This is a more sophisticated assessment tool, which integrates functionality from TI-Nspire Teacher Edition, where it is possible to create embedded questions in TI-Nspire student files. When the file is sent to the students, they answer it at their own pace and, on saving their TI-Nspire file on the handheld, their responses are saved. The teacher then collects the students' files using the TI-Nspire Navigator software and, on doing so, adds them to the class portfolio. This then facilitates the detailed analysis of the individual and group responses. Depending on the nature of the question type (open response, yes/no, etc.) and whether the teachers had identified a 'correct' answer, the results are displayed in different formats (Fig. 5).

5 Research findings

5.1 Overview

The analysis of the teachers' lesson evaluations ($n = 25$) and the supporting data enabled quantitative data concerning the uses of the different functionality to be concluded and an analysis of the nature of these uses to emerge. Many of these were not mutually exclusive in that they touched on several aspects of the TI-Nspire Navigator functionality. For example, a single lesson might integrate the use of a number of features and the teacher may not attribute the noticeable outcomes to any one particular aspect. The mathematical content of the lessons covered a range of topics: algebra ($n = 10$); geometry ($n = 10$); and statistics ($n = 5$) and, due to the wide age range of the students, these topics were approached at different levels of complexity (Fig. 6).

As an aim of the research to gain insight into the teachers' classroom practices, what follows is a brief description of the types of uses that the teachers developed for *Screen capture*, *Quick Poll* and *Live Presenter*.

Screen Capture was the most popular feature of TI-Nspire Navigator and it was used in 92% of the lessons with the teachers unanimously reporting very positive outcomes of its use in their classrooms, although they used it in different ways. The data analysis led to the following categories of use: monitoring students' activity during the lesson; supporting teachers to know when to intervene; promoting and initiating whole-class discourse; promoting and supporting peer and self- assessment; privileging mathematical generalization; increasing sample sizes

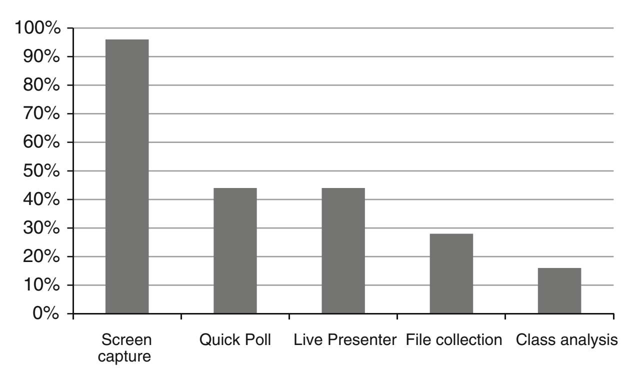

Fig. 6 Frequency of use of TI-Nspire Navigator features ($n = 25$)

(within statistical work); and enabling mathematical sorting.

Quick Poll was used in 11 of the reported lessons. Although no particular trends in use emerged from this fairly limited data, the range of uses for *Quick Poll* included: as a focusing act to initiate the start of lesson activities; the generation of data for use during the lesson; prompting class discussion on a particular mathematical feature, concept or fact; and checking students' understanding of a particular mathematical feature, concept or fact.

Live Presenter was also a popular feature of TI-Nspire Navigator and was used by all but one of the teachers (this teacher had rejected its use, as he felt that the refresh rate was too slow). The categories of use for *Live presenter* were sub-divided into 'use by teachers' and 'use by students' and included: teacher and student use to support the use of the TI-Nspire handhelds; teacher use to introduce and develop mathematical tasks; teacher use to generate data for use by the class; and student use to share mathematical observations, outcomes and insights.

5.2 An analysis of the teachers' uses in relation to 'desirable' classroom pedagogies and 'enhanced' student engagement and achievement?

The analysis of the emergent pedagogical practices that the teachers developed using TI-Nspire Navigator, supported by the teachers' rationales for these uses, revealed the following themes in relation to their perceptions of the changes in their classrooms as relevant to the aims of the research.

The teachers reported that TI-Nspire Navigator was used to:

- develop new and support existing formative assessment practices;
- enable the development of innovative mathematical tasks;
- support the use of the handheld technology for both individual and whole-class work;
- support teachers' lesson planning to include desired pedagogical approaches, lesson organization and classroom management strategies.

Whilst all of these aspects are important, the remaining discussion will focus on the first three bulleted points only due to the limitation of the length of this paper.

Developing new and supporting existing formative assessment practices for the purposes of this article, the following definition of formative assessment provided by Black and Wiliam (as an outcome of their extensive research into teachers' classroom practices over the last 2 decades) has been adopted,

> Practice in a classroom is formative to the extent that evidence about student achievement is elicited, interpreted, and used by teachers, learners, or their peers, to make decisions about the next steps in instruction that are likely to be better, or better founded, than the decisions they would have taken in the absence of the evidence that was elicited. (Black and Wiliam 2009, p. 9)

All of the teachers reported in their teachers' lesson evaluations that TI-Nspire Navigator provided an opportunity for the teachers and students to engage in a range of formative assessment practices. This finding was also triangulated with accompanying lesson observation data.

These practices could be described as:

- providing teachers with additional insight to enable them to provide thoughtful interventions during the lesson;
- promoting purposeful classroom discourse to enrich the teacher's awareness of students' existing mathematical knowledge;
- developing strategies for students' peer assessment and self-assessment.

Each of these practices is now described in further detail.

A variety of evidence was elicited about the ways in which the teachers used the system to support them to know when their interventions were needed to progress the students' mathematical learning.

- *Screen Capture* was used by the teacher to monitor students' work and identify both mathematical and technological issues 'before they escalated' [lesson evaluation]. Teachers were then able to target appropriate (differentiated) support either to individual students or the whole group, as appropriate.
- In response to identified observations of students' difficulties, teachers were able to 'help more students at a time' [lesson evaluation] using *Live Presenter.*
- In response to particular mathematical observations from *Screen Capture*, *Quick Poll* questions were sent to students to check opinions, facts and conceptual understanding.
- *Screen Capture* was used by the teacher to identify 'interesting screens' that could be used to increase students' active engagement in the lesson through the use of *Live Presenter* by identified students.

All of the teachers cited at least one example of how the use of the system had supported the quality of the mathematical discourse within the lesson. The term discourse refers broadly to the words that are spoken in the classroom by teacher and students, the nature of which can vary greatly from classroom to classroom. For some teachers, the aim was for this discourse to be less teacher dominated, where only one or two students respond to the teacher's questions. This could be achieved by including more opportunities for discussion by the students: for example, by asking students to discuss an aspect of the mathematics observed through the *Screen Capture* view with a fellow student and be prepared to give feedback of their opinions or hypotheses. The visibility of many TI-Nspire screens provided more to discuss in the classrooms and *Quick Poll* or embedded questions within the TI-Nspire files were also used to prompt the discourse.

Within the context of Black and Wiliam's definition of formative assessment, students' peer and self-assessment approaches include all of those practices whereby students position their own knowledge and understanding alongside those of their peers and, as a result of being exposed to other students' views and opinions (as well as the teachers), reposition their stance. The use of *Screen Capture* alone provided substantial evidence for how exposing students to the thinking of their peers, as evidenced by the snapshots provided in the *Screen Capture* view, had a noticeably positive impact on the students' lesson outcomes. Although this study was not designed to seek evidence of improved students' outcomes in mathematics, the teachers reported many examples where they noticed that students changed their opinion or moderated their responses as a result of both the passive and active sharing of students' outcomes. In the passive instances, *Screen Capture* was just displayed publicly in the background and students were free to look at it or ignore it. In the more active scenario, the teacher drew students' attentions to 'interesting screens', sometimes asking the owner of selected screens to share their thinking. In both scenarios, this provided opportunities for students to learn from their peers.

Cindy used a *Quick Poll* to initiate the mathematics task for the lesson by asking the students (aged 13–14 years) to send two numbers that when squared and added together gave a total of 25. The mathematics objective of the lesson was to introduce students to circle functions.

Students provided responses such as:

3^2 and 4^2

3 and 4

0 and 5

-3 and 4

The *Quick Poll* was set up to accept open responses and Cindy justified this use by saying that she wanted to 'promote individual thought' [lesson evaluation] (Fig. 7).

In her lesson evaluation, Cindy commented,

> The responses were then shared with the whole class and we scrolled down each one and comments were made about the results. I had given no guidance as to how to share solutions so there was a big array of answers. The majority included 3 and 4 as I had expected. A very few students had included zeros (are they allowed? I was asked). Also, one or two students included negative values. This prompted more discussion as to the values that were allowed. I then got them thinking in terms of x and y and constructing a graph of results.' [Lesson Evaluation)]

Fig. 7 Using *Quick Poll* to generate coordinate points that satisfy $x^2 + y^2 = 25$

Cindy displayed the students' handheld screens using *Live presenter* throughout the lesson to allow the students to see each other's progress through the task.

This prompted a significant moment in the lesson when students began to ask each other how they were managing to generate more and more points. This led to the mathematical appreciation that there were an infinite number of solutions, and by considering positive and negative surds

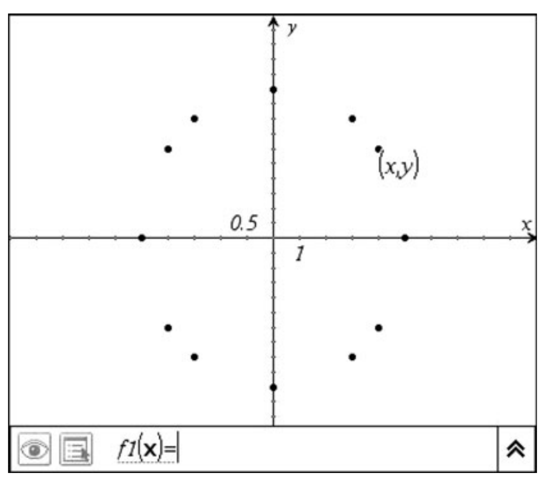

Fig. 8 Student A's response

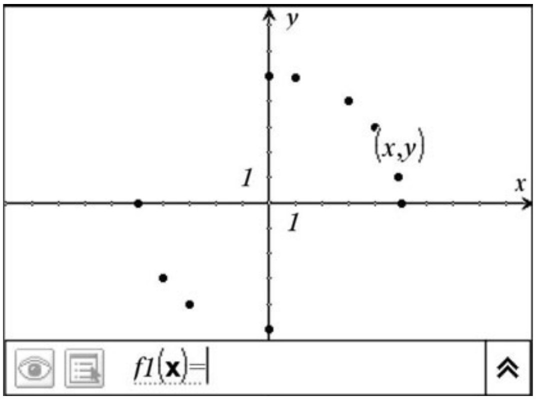

Fig. 9 Student B's response

(such as the pair $-\sqrt{11}$ and $\sqrt{14}$), the class developed a strategy that would achieve this (Figs. 8, 9). Cindy commented that she thought that, although she could have told the students to use this approach at the beginning of the task, it held more meaning for the class because it had emerged from one of the students and the rest of the class had then adopted the idea.

Quick Poll and *Class Analysis* responses and results were used publicly in a similar way to enable individual students to learn from the responses of others. One teacher commented on how allowing her students to see each others' responses (correct and incorrect) specifically supported the less mathematically confident students, as they were able to see that they were not the only students who were unsure how to respond.

Enabling the development of innovative mathematics tasks during the pilot project, a number of tasks were designed and pedagogic approaches devised, which used the TI-Nspire Navigator features in innovative ways. The term innovative is used because, although these approaches may exist within the wider research literature, they were not within the teachers' existing practices. In a few cases, these tasks elicited new approaches, which may not have been possible using commonly used resources for mathematics.

The most exciting of such an approach developed for the use of TI-Nspire Navigator related to the design of a number of tasks where *Screen Capture* was used to support students to arrive at mathematical generalizations. In these activities, the teachers had constructed TI-Nspire files, which required the students to change specific variables by dragging on-screen objects to meet certain constraints.

The following lesson, devised by Jay, provides a good example of this (all quotes are from the transcript of the lesson).

Jay wrote that his main objective for his lesson with his 13–14-year olds was 'for students to appreciate Pythagoras' Theorem, in particular recognizing that the sum of the areas of the squares on the two smaller sides will equal the area on the longer side if and only if the triangle is right angled'.

He also added a specific intention for the use of the wireless network, 'Each individual student will explore the triangles on their own handheld—we will use the shared space of screen capture to come to a shared agreement about the necessity for the triangle to be right angled'.

They began with an introductory task, which Jay used to check that they were all confident about selecting and dragging the vertices of squares and observing some resulting measured areas before asking the students to move to the screen shown below. The subtle design of this task was that the triangle had been constructed as a scalene triangle, which meant that as the students changed its properties, the resulting areas of the squares constructed on its sides varied.

Jay asked the students to drag the vertices of the triangle to a position where the areas of the two smaller squares (Jay gestured to these as 'a and b') summed to equal the area of the square he called 'c' (Fig. 10).

At this stage, Jay gave the students 5 min to respond to this challenge during which time he moved around the room supporting students and monitoring their activity. In this period, the students' handheld screens were on public display to the class, refreshing automatically every 30 s. Jay concluded this period of the lesson by alerting the students that they were going to be stopping and reviewing the class display of the individual handheld screens in a few minutes and that they would, 'scroll down and have a little chat about them and see how we're getting on'.

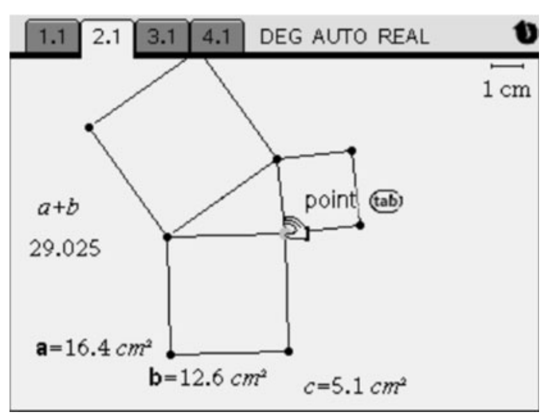

Fig. 10 Jay's Pythagoras task

At this point, he reminded the students that '…we're kind of looking at the ones that do work and the ones that don't…' and he invited the students to volunteer their screen number if they thought that their screen 'worked'. At this point, there was a noticeable increase in students' participation and involvement as a number of students were heard to call out 'mine works', '22 works' and 'mine's 12' and Jay tried to locate these screens and move them so that they were visible to the class.

Jay then directed the students by saying,

'Okay I'd like you to look at the ones that work that we've identified and compare them with the ones that don't work and I want you to look at the shape of the triangle… …in the middle. This is what I am asking you to look at now. Look at the shape of the triangle. Look at the ones that work, look at the ones that don't work and my question to you and you've 30 s to discuss this now, my question to you is, is there anything different about the shape of that triangle in the ones that work compared to the ones that don't quite work? You've got 30 s to talk about it'.

After a short period of pupil discussion, Jay asked if anyone had noticed anything and a student volunteered a response 'Is it right angled?'

Jay responded by displaying the following student's handheld screen (Fig. 11) and making the following comment, directed towards the owner of the screen:

Yours is quite easy to see isn't it?—that this is a right angled triangle because you've actually got a square and you can see it's a corner of a square in there—yes it is a right angled triangle.

Jay selected another student's screen (Fig. 12) and talked through why it did not 'work'.

Now this one here looks a little bit off, let's have a look at the numbers *a* add *b* is 15.7 and *c* is 19 so this one is a

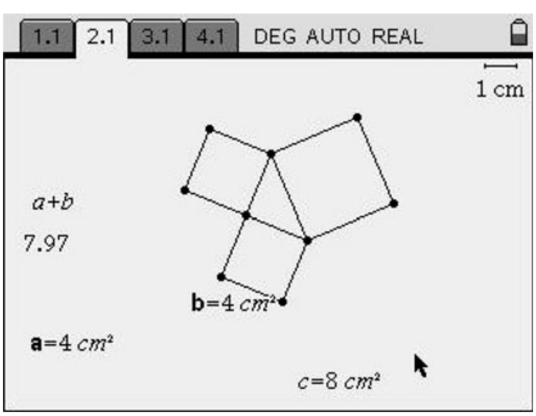

Fig. 11 Student C's response

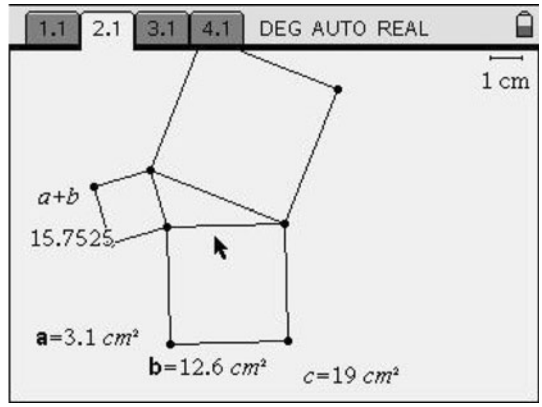

Fig. 12 Student D's response

little bit off—it is not a right angled triangle, it doesn't quite work.

Jay selected two more examples and spoke his thoughts out loud to reason through the calculation of the sum of the measured areas to verify whether they did or did not meet the initial task constraint. He then asked the students to make a conjecture by saying, 'So what do you think we are learning from this then? What do you think we are noticing about the ones that work and about the ones that don't work?'

The following dialogue ensued:

Student A: The more the equaller they get then… you know…

JT: The more the equaller they get then you know—okay, would you like to say that mathematically?

Student B: They've all got a right angle in them.

JT: They've got a right angle in them—so if the two small areas make the bigger area…

Student B: [interrupts] it makes a right angle

JT: You get a right angled triangle. Okay, so that's what we're learning here if the two smaller areas of our squares make the bigger area then we it's a right angled triangle. If it's a right angled triangle then the two smaller areas—of the squares—make…

Student C: [interrupts] the biggest area.

JT: the biggest area.

Jay concluded the lesson by giving the students the opportunity to record their findings in their own words. In his lesson evaluation, he expressed concern as to whether the students had appreciated the importance of the 'special case' of the right-angled triangle and planned to return to this in a subsequent lesson.

In this lesson, the public display of the student' screens supported the teacher and students to notice similarities and differences between the various outcomes and to focus on the common mathematical features or aspects of the task. The wide variety of responses provided both a global view of the mathematics under scrutiny, in addition to the individual student's local view.

Supporting the use of the handheld technology for both individual and whole-class work the lesson example that has just been described also exemplified how the networked system supported whole-class work. Several other teachers were also very enthusiastic about the way that the use of *Screen Capture* supported the notion of a 'shared learning space' in which each student had a sense of ownership with respect to their own screen and an appreciation of how their screen fitted into the bigger picture or 'global view' previously mentioned. This view was supported by some of the students interviewed, one of whom said 'We feel good to be seen in the screen by the all class. It is a bit embarrassing if you are wrong but we are human beings. I [We] can be supported by friends if I'm wrong' [student interview]. Another student said 'You really want to know who you are in the screen capture' [student interview]. It was noticeable that, in the pilot classes, *Screen Capture* was used with the students' names showing, enabling both the students and teachers to know whose screen was whose. A consequence of this shared learning space was that the teachers were able to open *Live Presenter* to take up the students' own suggestions with respect to the task and this also seemed to encourage the students to begin to pose their own mathematical questions. One teacher gathered responses from his whole class about their perceptions of the TI-Nspire Navigator system, which also provided good evidence of the students' appreciation of how seeing each others' screens supported their learning.

There were two examples where TI-Nspire Navigator had been used to generate the mathematical data to initiate the task with which the students were to engage. Cindy's lesson using *Quick Poll* was such an example. She used it to elicit students' responses to an open mathematical question to enable a wide number of answers to stimulate the students' thinking. In a second example the teacher's handheld was connected to a temperature probe and *Live Presenter* used to carry out a data collection experiment at the beginning of the lesson. File transfer was then used from the teacher's handheld to distribute the date quickly and efficiently to the students' handhelds and facilitate a mathematical modelling task.

Two teachers provided examples of the use of TI-Nspire Navigator to enhance statistical work in mathematics by using the *Screen Capture* view to increase the visible sample size of the class data. This was used to support students' understanding of the relevance and importance of sample size when drawing assumptions from statistical data and also to appreciate the way in which the TI-Nspire Random number generator and RandSeed setting influenced the resulting data when simulating dice experiments. One of the teachers commented that 'the *capture everyone's simulation results graphically* approach is a route I'd be interested in seeing if there are other topics of maths that could benefit from this sort of approach'.

6 Emerging issues relating to the use of networks of handhelds

Although, as previously stated, the classroom evidence provided by the teachers was resoundingly positive about the wireless handheld network, there were a number of issues that emerged that are worthy of a deeper discussion.

6.1 Responding to increased amounts of lesson data

One teacher wrote that, although he had collected a series of students' screenshots throughout the lesson, he did not know if and how it would be useful to him. In his evaluation he wrote, 'the fact that I have 'taken in' their work at the stage it's at and it's in a form that I can share back with them is something of great potential (but still to be proven). It's not possible to take in all their jotters, photocopy all of their workings/discoveries and then re-share around the room, which is effectively what's going on here' [lesson evaluation]. This suggests that teachers may need to develop new strategies for managing the increased amounts of data concerning their students' progress that the wireless system can generate throughout a lesson: for example, by scanning rather than scrutinizing students' files or screenshots to identify similarities and differences in the students' responses. Selected screens might then become the focus for the initial classroom discourse at the beginning of the subsequent teaching session. The issue of dealing with increasing amounts of data is not new within the field of interactive computer-aided learning, and it is possible that the mathematics education research community can draw on this field of research (Diem Pham Thi et al. 2009, Laurence 2009).

6.2 Managing the change in the classroom ethos

It is undeniable that the introduction of the TI-Nspire Navigator system to the mathematics classroom impacts upon the learning environment and imposes new ways of working for both the students and the teacher. Several teachers spoke about the need to have the 'right ethos' in the classroom whereby TI-Nspire Navigator was seen predominantly as a tool to support students' learning rather than for teacher's monitoring and assessment. Teachers described this ethos in ways that resonated with Hiebert et al.'s definition of an 'effective' classroom ethos in which all student contributions are valued, their mistakes are used as learning sites and there is a sense of correctness, which resides in the quality of the mathematical argument (Hiebert et al. 1997).

Another teacher spoke of the need to support students to meet new expectations of them in relation to what mathematics is and how they might engage with it. For example, Cindy spoke of her students not knowing how to respond to an 'always/sometimes/never' question in a mathematical context and identified that, the next time she used one, she would spend a few minutes discussing with the students how to respond to such a question. In one reported lesson, the teacher wrote that a student had asked 'Is this coming back in the written test' [lesson evaluation] suggesting that a renegotiation of the didactic contract between the teacher and students was being provoked by the use of the technology.

The teacher who used the *Class Analysis* feature within a lesson to give feedback on the outcomes of a class quiz was explicit in telling his students that he was 'not going to point the finger' at them, but use the results to remind them of mathematical facts that he thought they should already know.

6.3 Implications for the role of the teacher

A number of implications for the role of the teacher were identified from the teachers' own writings, which were highly reflective and thoughtful on this issue. Several of the teachers talked about noticeable changes in their role with respect to managing the mathematics classroom when *Screen Capture* was being used, particularly concerning their perceived need to be able to respond quickly to the diversity of screens that were visible.

One teacher wrote about his slight discomfort about being 'on show' in front of the class more than was usual and another of his perception that he needed to be able to make sense of all the different student responses very quickly to plan the next stage of the activity. This resonates with Sinclair's finding that 'Dealing with a wide range of student responses requires deep knowledge of the subject matter' (Sinclair 2008, p. 34).

Similarly, when considering how they might develop their use of *Class Analysis*, several teachers commented on the need for them to ensure that they had thought through the students' possible responses and included the right sort of *Question and Answer* format within any embedded questions.

One teacher wrote early on in the project about how the evidence gained from *Screen Capture* alone had prompted him to slow his teaching down and that he had realized that the pace at which his students could take up mathematical ideas differed from his earlier perception. This implies that teachers may need support to reconsider their expectations of their students and the implications on the notion of 'pace' when planning their TI-Nspire Navigator lessons.

7 Conclusions

The pilot project's aims were to collate evidence about the aspects of the classroom use of TI-Nspire Navigator that promoted desirable classroom pedagogies and the nature of the mathematical starting points that led to enhanced student engagement and achievement in mathematics.

The analysis of the use of the system's functionality concluded that the use of *Screen Capture* was widely used by all of the teachers involved in the study. Although there were less frequent uses of *Quick Poll* and *Live Presenter*, the supporting evidence for these uses was relevant with respect to the research aims, which is in direct contrast to the uses of the *File Collection* and *Class Analysis* functionality.

To summarize, the main findings of the research reported in this article concerned:

- The development of new (and support for existing) formative assessment practices by: providing teachers with more insight into their students' sense-making processes, and leading to more thoughtful teacher interventions; promoting meaningful mathematical classroom discourse, prompted by shared responses and screens; and, as a result of the previous two practices, increasing opportunities for purposeful students' self- and peer assessment.
- Enabling teachers to develop innovative mathematical tasks and approaches, which included: the use of multiple handheld screens within *Screen Capture* to support mathematical generalizations; the use of the students' screens as objects that can be sorted according to mathematical criteria; and the use of the students' screens to increase the sample space of data or ideas. The term 'innovative' is used because, in all cases, these were not approaches that the teachers had used previously in their classrooms.

Indeed for those teachers for whom TI-Nspire was an existing tool in their mathematical toolkit, TI-Nspire Navigator offered a natural progression towards the collaborative classroom environment that most of them said that they valued.

Evidence from this study has suggested that within the TI-Nspire Navigator environment, an important aspect of a teacher's role is that of mediating the students' learning. The window into the students' thinking that TI-Nspire Navigator provides acts as a support for this, by allowing the teacher to see more deeply than previously, whilst also providing a threat to the teacher as they find themselves more exposed in front of the class.

Further research is needed in the following areas to:

- elicit evidence of the teachers' professional development journey with TI-Nspire Navigator over a longer timescale with a view to providing evidence of their uses of *Class Analysis* and *File collection and redistribution*;
- explore the classroom experiences of 'average' mathematics teachers who did not necessarily have any experience of using the TI-Nspire handhelds or TI-Nspire Teacher Edition software;
- begin to evidence the impact of the use of TI-Nspire Navigator with students on their perceptions of mathematics, attitudes towards mathematics and, ultimately, their mathematical achievements.

Appendix 1: Teaching with TI-Nspire Navigator—case study report

Name:	Date:
School:	Class (and year):
Mathematics level:	Number of students:
During this mathematics lessons I used: *(please highlight)* File Transfer Screen Capture Quick Poll Class Analysis Other *please describe*	**For the follow up mathematics homework my students used:** *(please highlight)* Only TI-Nspire handheld device Only TI- Nspire software on a PC Handheld and Software TI- Nspire Neither

Describe your planning for the lesson

What mathematics did you want the students to learn?

Describe the TI-Nspire Navigator activity that you developed.

How did you plan to use TI-Nspire Navigator during the lesson?

Please list the files (TI-Nspire, Screen Capture, video) that accompany this lesson.

Now, describe what actually happened. Please be as detailed as you can, particularly in relation to *when* and *how* you used Screen Capture and/or Quick Poll.

How did you introduce the activity?

What were students' initial reactions/questions?

Approximately, how many of the students could develop strategies to fully pursue the activity with little or no guidance from you?

What, if any, guidance did you have to give to the students?

Please indicate how the use of Screen Capture and/or Quick Poll supported you to identify and respond to students' difficulties.

Give examples of the sort of interventions you made, in particular how you used Screen Capture and/or *Quick Poll* to support these interventions.

Now, please evaluate the students' mathematical learning during the activity.

Give a brief summary of the students' work/outcomes in relation to:

Representing mathematics

e.g. *identifying the mathematical aspects of the situation or problem; choosing between representations; simplifying the situation or problem to represent it mathematically using appropriate variables, symbols, diagrams and models; selecting mathematical information, methods and tools for use.*

Analysing mathematics

e.g. *making connections within mathematics; using knowledge of related problems; visualizing and working with dynamic images; looking for and examining patterns and classifying them;*

making and justifying conjectures and generalizations; considering special cases and counterexamples; exploring the effects of varying values and looking for invariance; taking account of feedback and learning from mistakes; working logically towards results and solutions, recognizing the impact of constraints and assumptions; appreciating that there are a number of different techniques that can be used to analyse a situation; reasoning inductively and deducing results.

Using appropriate mathematical procedures

e.g. *making accurate mathematical diagrams, graphs and constructions on paper and on screen; manipulating numbers, algebraic expressions and equations and applying routine algorithms; using accurate notation, including correct syntax when using ICT; recording methods, solutions and conclusions; estimating, approximating and checking results.*

Interpreting and evaluating mathematics

e.g. *forming convincing arguments based on findings and making general statements; considering the assumptions made and the appropriateness and accuracy of results and conclusions; being aware of strength of empirical evidence and appreciating the difference between evidence and proof; looking at data to find patterns and exceptions; relating findings to the original context, identifying whether they support or refute conjectures; engaging with someone else's mathematical reasoning in the context of a problem or particular situation; considering whether alternative strategies may have helped or been better.*

Communicating and reflecting on mathematics

e.g. *communicating findings in a range of forms; engaging in mathematical discussion of results; considering the elegance and efficiency of alternative solutions; looking for equivalence in relation to both the different approaches to the problem and different problems with similar structures; making connections between the current situation and outcomes, and ones they have met before.*

In your view, did the use of TI-Nspire Navigator enhance the students' mathematical learning experience?

If yes, what evidence would you use to support this?

Now please say a little about what you have learnt about using TI-Nspire Navigator from this activity.

Can you comment on how the use of Screen Capture and/or *Quick Poll* supported you to formatively assess the students' mathematical progress *during* the lesson? *Describe any examples of how you used the system and how it changed your actions as a teacher.*

What aspect(s) of the idea would you use again?

What changes would you make?

Any other observations…?

pupils' comments…?

other teachers' comments…?

Appendix 2: Data codes

Promoting mathematical discussion.

Providing opportunities for students to present and explain their work to their peers.

Supporting the teacher's introduction to the mathematical task.

Generating live data in the classroom.

Providing opportunities for students to pose mathematical questions to each other.

Stimulating the mathematical task by the collection of students' responses.

Initiating the lesson by using a motivational prompt to the class.

Elicit the students' views concerning the mathematics midway through a task.

Sharing students' early responses to tasks as a means of stimulating other students' thinking.

Involving the students in determining the direction of the mathematical tasks.

Providing teachers with information that helped them to know when to intervene to support students.

Providing teachers with 'interesting examples' about which to structure the classroom discourse.

Enabling teachers to monitor the students' task outcomes privately.

Enabling teachers to monitor the students' task outcomes publicly.

Using the students' screens as objects that can be sorted according to mathematical criteria.

Using the students' screens to increase the sample space of data or ideas.

Supporting students to learn from each other's ideas and approaches.

Providing teachers with a deeper insight into how their students were learning mathematics.

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