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How to Flip the Classroom – "Productive Failure or Traditional Flipped Classroom" Pedagogical Design?

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ABSTRACT

The paper reports a quasi-experimental study comparing the "traditional flipped classroom" pedagogical design with the "productive failure" (Kapur, 2016) pedagogical design in the flipped classroom for a 2-week curricular unit on polynomials in a Hong Kong Secondary school. Different from the flipped classroom where students are provided video clips with new concepts and associated procedures to review at home before solving problems in class, the "productive failure" pedagogical design in the flipped classroom worked the other way around. Supported by mobile technologies, students explored, discussed and solved problems related to the new concepts first in class even though they might come across failures, followed by consolidating the concepts and associated procedures using video clips at home. The pedagogical design is referred to as "productive failure-based flipped classroom" in this study. The study was carried out in two Grade 7 classes: one with "traditional flipped classroom" and one with the "productive failure-based flipped classroom". Findings show that both classes had significant improvement in procedural knowledge. However, regarding conceptual knowledge, students in the "productive failure" condition performed better than those in traditional flipped classroom. This suggests that the "productive failure-based flipped classroom" pedagogical design may be better able to improve students' problem solving skills.

Keywords

Productive failure-based flipped classroom, Traditional flipped classroom, Procedural knowledge, Conceptual knowledge, Mathematics learning

Introduction

The flipped classroom has gained prominence in recent years. There is no uniform definition of it. The traditional flipped classroom in this paper refers to the pedagogical design that inverts the teacher's instruction in the classroom out of formal class time and uses class time for students to actively engage in practice and knowledge construction with technology support (Baepler, Walker, & Driessen, 2014). A review of the literature shows that the approach adopted, in many cases, intends to make use of videos as lecture instruction out of class time, thus affords more classroom time to engage students in active learning (e.g., Charles-Ogan & Williams, 2015; Chen, Yang, & Hsiao, 2015; Jungić, Kaur, Mulholland, & Xin, 2015; Moore, Gillett, & Steele, 2014; Muir & Geiger, 2015; Sohrabi & Iraj, 2016; Wasserman, Quint, Norris, & Carr, 2015). However, it appears that the traditional way of instruction (direct instruction) remains unchanged except that the time spent on the lecturing in class is performed at home. How to enhance students' conceptual understanding and develop their problem solving skills in the design and implementation of the flipped classroom has rarely been addressed.

How to flip the classroom? The paper reports a quasi-experimental study comparing the "traditional flipped classroom" pedagogical design to the "productive failure" pedagogical design in the flipped classroom for a 2-week curricular unit on polynomials in a Hong Kong Secondary school. Productive failure is defined as "a learning design that affords students opportunities to generate representations and solutions to a novel problem that targets a concept they have not learned yet, followed by consolidation and knowledge assembly where they learn the targeted concept" (Kapur, 2015, p. 52). In the "productive failure" pedagogical design, students explored, discussed, and solved problems related to the new concepts first in class even though they might come across failures, followed by consolidating the concepts and associated procedures using video clips at home supported by mobile devices. The pedagogical design is referred to as "productive failure-based flipped classroom" in this study.

The rest of the paper reviews the literature, followed by research methods. Then the results are presented and discussed.

Relevant literature

“Traditional flipped classroom” pedagogical design

The flipped classroom is also termed as “inverted classroom” or “blended learning” with various definitions (Chen, Wang, Kinshuk, & Chen, 2014). In general, the flipped classroom attempts to free student class time from lectures by providing the new instructional content (including concepts) in the form of video-clips for students to watch as homework; then use class time for active learning where the teacher acts as a facilitator to organize class activities to deepen their conceptual understanding (Roehl, Reddy, & Shannon, 2013). This type of pedagogical design is referred to as “traditional flipped classroom” and is used interchangeably with the flipped classroom in this paper. Active learning is known as any instructional method that engages students in their learning process through collaborative and problem-based learning activities to develop their critical thinking and problem solving skills (Prince, 2004). Although teacher-student contact hours do not change, students can re-play the instructional content at home, and have more teacher-student engagement in class. The ultimate goal is to shift teacher-centered instruction to student-centered learning to change the role of the teacher from *a sage on the stage to a guide on the side* (King, 1993).

The flipped classroom is gaining popularity. Previous studies have typically been conducted in higher education settings (e.g., Abeysekera & Dawson, 2015), and in recent years, research on the flipped classroom in school education is on the rise, particularly in mathematics learning and teaching (Muir & Geiger, 2015). The findings are mixed. Some research findings show that flipped learning encourages students to take a more active role in the learning process before and during the class time (Jungić, Kaur, Mulholland, & Xin, 2015); it increases student motivation and satisfaction with their learning (Clark, 2015; Muir & Geiger, 2015; Hernandez-Nanclares & Perez-Rodriguez, 2016; Love, Hodge, Grandgenett, & Swift, 2014); it allows students to learn at their own pace be responsible for their own learning (O’Flaherty & Phillips, 2015; Lai & Hwang, 2016); it provides an opportunity for differentiated teaching for a range of students’ abilities (Herreid & Schiller, 2013); it has the potential to increase students’ learning performance gains (Heyborne & Perrett, 2016); and the affordances of the flipped classroom approach provide an option for mathematics teachers to address the challenges of the twin demands of covering the prescribed curriculum and catering for students’ learning needs (Muir & Geiger, 2015).

However, some studies show that there are no significant improvements of knowledge gains in students’ learning in flipped learning compared to traditional way of learning in mathematics, and students perceptions of the flipped learning are mixed either in school or higher education (Clark, 2015; Love et al., 2014; Wasserman, Quint, Norris, & Carr, 2015). This indicates that flipped classroom may not be applicable to all subjects (O’Flaherty & Phillips, 2015). DeLozier and Rhodes (2016) posit that video instruction as homework itself in the flipped classroom does not appear to result in changes in learning performance, but may provide additional time for in-class active learning activities that enhance learning performance through different learning activities such as student discussions, collaborative activities and presentations. Students particularly appreciate collaboration and instructional video components in the flipped classroom (Love et al., 2014). O’Flaherty and Phillips (2015), reviewing the literature in flipped learning, point out that existing research under-utilizes conceptual frameworks and pedagogical designs in the flipped classroom, and lacks better integration of pre-class activities into face-to-face classes with active learning pedagogies to develop students’ higher order thinking skills such as improved problem solving, inquiry and critical or creative thinking. They also recognize the need for stronger evidence in evaluating student outcomes in the flipped classroom.

Issues

Despite that there are a number of recent studies on the flipped classroom to enhance student active learning, the majority of the studies have reported the practices in higher education and the findings are mixed, and how to design the learning activities to promote active learning is still at a nascent stage (e.g., Abeysekera & Dawson, 2015; O’Flaherty & Phillips, 2015). Few studies have reported how to develop school students’ problem solving skills and enhance their conceptual understanding in flipped classroom in mathematics inquiry. In addition, the pedagogical design adopted in the flipped classroom, in many cases, intends to be in direct instructional mode, in which students make use of videos as lecture instruction out of class time and practice activities in class time, but are lack of theoretical framework to guide the design and implementation of the learning activities.

In mathematics education, inquiry-based learning is advocated to develop students’ problem-solving skills and enhance their conceptual knowledge (Curriculum Development Council, 2015). Students are typically involved a set of inquiry phases such as engage, explore, explain, extend and reflect processes (Krajcik, Blumenfeld, Marx,

& Soloway, 2000; Marshall & Horton, 2011; Song, 2014). However, in the flipped classroom, the focus is to move lecture tasks to be performed at home, and leave more time for practice and discussion in class. It appears that the traditional way of instruction (direct instruction) remains unchanged except that the time spent on the lecturing in class is performed at home. Thus, existing flipped classroom approach does not seem to leave room for students to "engage" and "explore" the new knowledge/concepts, but transmits the new knowledge to them via video-based micro lectures to be reviewed beyond classroom. This does not mean that direct instruction is useless and does nothing good to learning. On the contrary, "direct instruction does a fairly good job" if the learning goals are oriented to the acquisition of basic knowledge for problem solving without obtaining corresponding conceptual understanding and knowledge transfer (Kapur, 2016, p. 8). However, O'Flaherty and Phillips (2015) postulate that the successful flipped classroom implementation outcomes should take into account effective student learning that fosters problem solving skills and student engagement both within and beyond the class. They call for better integration of face-to-face learning activities and resources with pre-class ones adopting active learning pedagogies in order to motivate students to learn.

In light of the above issues, this study proposes to "restructure" the classroom and explore new ways to flip the classroom in order to enhance their conceptual understanding.

"Productive failure" pedagogical design

"Productive failure" pedagogical design first engages students in unguided problem solving to elicit their prior knowledge, particularly in the failure to solve the problem, followed by using this information to consolidate and aggregate new knowledge (Kapur, 2016). The failure stems from the fact that learners are commonly unable to generate or discover the correct solution to the novel problem by themselves; on the other hand, they are able to generate sub-optimal or even incorrect solutions to the problem, the process can be productive in preparing them to learn better from the subsequent instruction that follows (Kapur, 2014a; Kapur 2014b). This echoes the findings from Granberg's (2016) study on mathematics problem solving in secondary school education: if students who observe their errors and engage in productive struggles strive for exploring and analyzing the problems in mathematics, their struggles are likely to be productive in constructing new knowledge; on the contrary, if students who observe their errors and engage in unproductive struggles and do not go back to explore and analyze the problems, their struggles may be unproductive.

Kapur (2010) also compared "productive failure" instructional design with a traditional "lecture and practice" instructional design on the curricula unit of rate and speed in a Singaporean secondary school. The research findings show that students from the productive failure condition significantly outperformed their counterparts from the lecture and practice condition in the post test on procedural knowledge, and conceptual understanding and problem solving skills. Similar findings were also obtained in (Kapur, 2014a; Kapur 2014b) study on teaching the topic of concept and procedures of standard deviation, and Kapur and Bielaczyc's (2012) study on learning the concept of average speed in secondary education.

The aim of this study was to conduct a quasi-experimental study to test the effectiveness of the two pedagogical designs in the flipped classroom, one with "productive failure" pedagogical design, and the other with traditional direct instruction pedagogical design for mathematics learning in a Hong Kong secondary school on developing students' procedural knowledge and conceptual understanding of mathematical concepts. The next section presents the research methods, followed by the presentation of the research results, and discussions. Finally, a conclusion is drawn from this study.

Research methods

Proposed "productive failure-based flipped classroom" pedagogical design in this study

Premised on inquiry-based learning models (e.g., Hakkarainen, 2003; Krajcik et al., 2000) and adapted from productive failure four core learning design mechanisms (for fuller details, see Kapur & Bielaczyc, 2012), this study proposes a "productive failure" pedagogical design with a two-phase design. They are: Phase I Problem-solving (*Engage, Explore* and *Explain*) to be conducted in the classroom in groups; and Phase II *Consolidate* (video watching) to be conducted out of classroom individually (see Figure 1). In Phase I, "engage" concerns activation and differentiation of prior knowledge related to the targeted concept, "explore" relates to attention to critical conceptual features related to the targeted concept, and "explain" focuses on explanation and elaboration of these features related to the targeted concept. In Phase II, "*consolidate*" provides students the opportunities for organizing and assembling features related to the targeted concept. The learning activities are to be carried out in a mobile learning environment where students are encouraged to use their own mobile devices to support their learning both in and out of school and throughout the learning process (e.g., Song, 2014).

The new pedagogy using productive failure pedagogical design is flipped in terms of the learning design where students' problem-solving goes before the instruction, which contrasts with the learning design of flipped classroom where direct instruction via video clips is assigned as homework task first, followed by more challenging problem solving activities in class. We termed the novel pedagogy using productive failure design in a mobile learning environment as "*productive failure-based flipped classroom*" which has two connotations: (a) the new design of instruction adopts productive failure strategy; (b) the Consolidate (video-watching) Phase that used to be put at the beginning of the learning activities in flipped classroom using direct instruction is "flipped" to follow the Problem-solving Phase using "productive failure" pedagogical design in the new pedagogy.

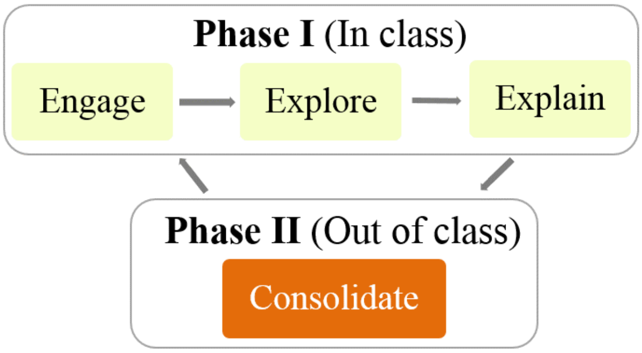


Figure 1. "Productive failure-based flipped classroom" pedagogical design

Participants

The study was conducted at a Secondary School with participants of 11 to 12-year olds from two 7^{th} grade classes with the class size of 25 students each. One class adopted "traditional flipped classroom" pedagogical design, which was termed as TFC group; the other class adopted the "productive failure-based flipped classroom" pedagogical design, which was termed as PFFC group. The TFC group had a mean score of 48.35 (SD = 17.38) in the entrance test, while the PFFC group had a mean score of 46.75 (SD = 18.31). The mean scores of the two classes had no significant differences (t = 0.32, df = 48, p > .05). They were students with better learning motivation and higher learning abilities. Each class was divided into 7 groups with 3 to 4 members. Individual differences of the group members were taken into account while grouping the students as some research findings show that mixed ability-based grouping can help improve students' academic performance (e.g., Boaler, 2008). Two experienced male teachers with around 10 years' of working experience led the TFC and PFFC groups. Both teachers were enthusiastic about adopting innovative pedagogies in their pedagogical practices and had participated a few seminars and workshops related to flipped classroom pedagogical practices and the productive failure pedagogical design. The concept of polynomials is typically included in the 7^{th} grade curricula unit in mathematics, and therefore, students had no learning experience of the concept.

Learning platform and mobile devices

In addition to the use of customized teaching materials in class, a learning platform – Socrative and Samsung tablets were adopted to engage students in learning. Socrative is a real-time online feedback system where teachers prepared questions beforehand and students took part in in-class activities with their mobile devices. After logging in and answering the questions assigned, students could get immediate results showing the correct answers as well as performance statistics. Twenty-six Samsung tablets were borrowed from school with build-in applications that allow whole-class screen sharing for students to provide immediate response on the monitor for all to view; group screen sharing that enables students from different groups to share their thoughts with one another, and screen monitoring and locking for teachers to keep track of what students were working on.

Research design

The PFFC group adopted the "productive failure-based flipped classroom" pedagogical design in which the first phase involves problem-solving activities in terms of "engage, explore and explain" in class and the second phase took place anywhere outside school where students consolidated the concept concerned with the mathematical concept related to polynomials. In Phase I, exploiting productive failure pedagogical design, the students were encouraged to work in groups trying to come up with different solutions while they were exploring, discussing and sharing in class. The elements of "engage, explore and explain" were used as scaffolds to facilitate collaborative problem solving activities, but without content-related guidance. This was followed by Phase II in which students consolidated the concepts involved in a particular topic through watching video clips at home individually.

The TFC group adopted the "traditional flipped classroom" pedagogical design, reversing the order of direct instruction from "teachers lecturing in class" and "students working on homework at home" to "students watching video clips with instructional content at home" as the first phase and "students' practice and solving problems with their team members with teachers' guidance" as the second phase. The empirical study involved 10 lessons (5 double lessons) spanning over 2 weeks. The pedagogical designs of the two pedagogical learning activities in the TFC group and PFFC group are shown in Figure 2.

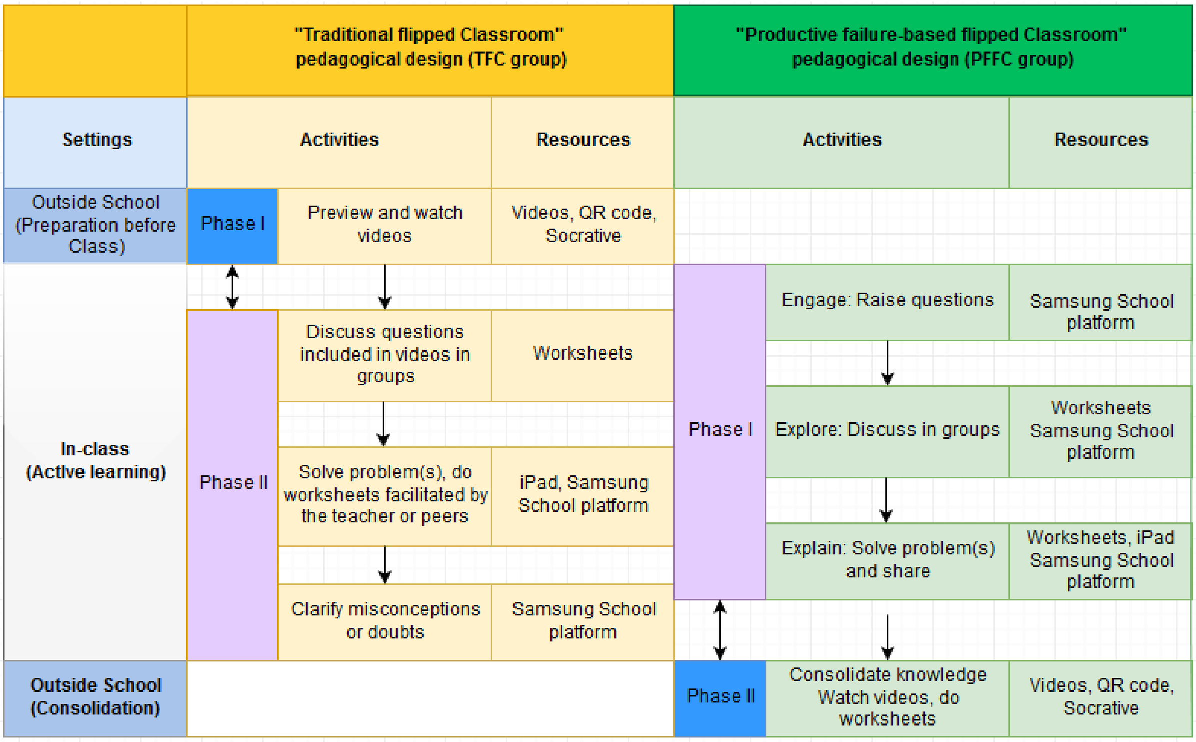


Figure 2. Pedagogical designs for TFC group and PFFC group

Figure 2 shows that the TFC and PFFC groups had the same length of pedagogical practices except for the differences in the time for watching the video clips. The two groups used the same videos consisting of 5 video clips, each with approximately 10 minutes in length. The content of the videos was co-designed by the two school teachers, and recorded using Microsoft Office Mix with various examples to illustrate ideas covered in each lesson. The first video was about the basic concept of algebra, exponential notation, and conversion between text and algebraic; the second went over the basic definition of powers, like terms and unlike terms; the third one was to do with the understanding of monomials and polynomials, arranging in ascending or descending order of powers and addition and subtraction of polynomials; the fourth one is about the multiplication and division of monomials, and the fifth one, also the last one was concerned with multiplication of polynomials. After the students finished watching the video clips, a hardcopy worksheet was distributed to students with a QR code that linked to the video clips on the Socrative learning platform for students' easy access via QR code reader app.

Before enacting the pedagogical activities, the researcher explained the aims of the study, reviewed the traditional flipped classroom pedagogical design and explained the new pedagogical design with productive failure via emails to the two teachers. Then we arranged two 2-hour professional development meetings with the teachers on principles of the pedagogical design, and the design of pedagogical activities and methods of carrying out the study.

Data sources and analysis

Data sources and analysis

Data sources includes pre-, mid- and post-domain tests, the post-conceptual understanding questions, focus group discussions and student survey about their video-clip watching activities regarding location, frequency and devices used. Pre-test was designed to test students' prior knowledge on the topic of "polynomial" before they started learning the topic with 9 questions; the level of difficulty was low and the content covered the whole unit of polynomial. Mid-test was designed to test students' mastery of various knowledge related to algebraic after having watched 3 teaching videos (after 6 lessons) with 10 questions; the level of difficulty was fair. Post-test was designed to test students' understanding of the content knowledge immediately after they learned the whole unit on "polynomial," especially addition and multiplication of polynomials with 10 questions; the level of difficulty of the test was comparatively higher than the previous two. The pre-, mid and post-tests focused on testing students' procedural knowledge gains. In addition, in the post-test, 3 conceptual understanding questions were used to test students' conceptual knowledge gains.

Focus group discussions had three questions: (1) Can you describe the learning activities in learning Polynomials? (2) How do you find the learning activities? Why? (3) What do you think is most important in your mathematics inquiry process? Student survey was conducted in class immediately after the post-test using a hardcopy questionnaire. All students (26 in total) in the TFC group completed the questionnaire; while, in the PFFC group, we collected 21 responses because 4 students provided medical certificates and were absent from class.

Data analysis

Both quantitative and qualitative methods were adopted in the data analysis. Table 1 summarizes the data sources and data analysis to address the questions of (a) the effectiveness of the pedagogical design intervention on students' procedural knowledge gains; and (b) the effectiveness of the pedagogical design intervention on students' conceptual knowledge gains. SPSS quantitative data analysis software and Excel were adopted in the data analysis. We also chose some examples to demonstrate students' learning in the two groups. The data related to conceptual understanding questions were analyzed separately from the rest of the post-test questions. Content analysis (Miles, & Huberman, 1994) was adopted for focus group discussions to understand students' perceptions of the two pedagogical models for their learning.

Table 1. Data sources and analysis

Data source	Data analysis	Effectiveness of pedagogical design intervention on development of	
		(a) procedural knowledge	(b) conceptual knowledge
Video-clip watching data	Quantitative	x	x
Pre-domain test	Quantitative	x	
Mid-domain test	Quantitative	x	
Post-domain test	Quantitative	x	
Post-test on conceptual understanding	Quantitative		x
Focus group discussions	Qualitative	x	x

Research results

Survey results about video-clip watching activities

In order to compare the learning performance between the TFC and PFFC groups, first of all, we analyzed the survey results about their video clip watching activities, which is shown in Table 2.

Table 2. Results of students' video watching activities (TFC and PFFC groups)

	Have you watched the videos?		How many times have you watched?			Where do you watch the videos?			On what device do you watch the videos?		
	Yes	No	1	2	3 or more	Home	Bus	Other	Smart Phone	Tablet	Computer
TFC group	100%	0%	46.2%	34.6%	19.2%	92.3%	3.9%	3.9%	73%	13.5%	13.5%
PFFC group	100%	0%	57.1%	23.8%	19.1%	100%	0%	0%	52.4%	23.8%	23.8%

Table 2 shows that 100% of the students in both groups watched the video clips, and almost all the students watched them at home. However, regarding "How many times have you watched each video clip?", it is found that 53.8% of students in the TFC group and 42.9% of students in the PFFC group watched the video clips 2 or 3 times. The χ^2 test shows that χ^2 equals to 0.745 ($df = 2$), $p < .05$. The results indicate that the two groups have significant difference in the distribution of times in watching the video clips. Another interesting phenomenon is that 27% of students in the TFC group and 47.6% of students in the PFFC group used tablets or desktop computers/laptops to watch videos ($\chi^2 = 0.75$, $p < .05$). The difference between the two groups is significant.

Impact of pedagogical design on students' procedural and conceptual knowledge

To understand the effectiveness of the "productive failure-based flipped classroom" pedagogical design, the results of pre-, mid-, post-test, and conceptual understanding' test scores (Full mark is 100 for each) of the TFC and PFFC groups were presented in Table 3.

T-test results show that no significant difference is found between the performance of the two groups on the three time points except conceptual understanding test (Pre-test: $t(1,48) = 1.047$, $p > .3$; mid-test: $t(1,48) = 1.515$, $p > .1$; post-test: $t(1,48) = 0.626$, $p > .5$; conceptual understanding: $t(1,48) = -2.089$, $p < .05$). Referring to the mean scores of each group in these tests, there appears to exist an interaction effect between the tests and groups. However, since the contents of the four tests are different, the score difference between those tests may not suggest the same meanings.

Table 3. The mean scores and *SD* of the four tests

	Pre-test		Mid-test		Post-test		Conceptual understanding	
	Mean	*SD*	Mean	*SD*	Mean	*SD*	Mean	*SD*
TFC group	25.48	14.16	46.74	21.74	39.71	28.45	37.64	28.11
PFFC group	21.84	10.30	37.54	21.63	34.90	26.34	52.57	22.76

In order to compare the scores of the four tests in the two groups on a same scale, the original scores were standardized by transforming all of them to T scores, and then used them for further statistical analysis. The T score is calculated based on the Z score, with an overall average of 50, and a standard deviation of 10. Figure 3 shows the mean T scores of the four tests in both groups.

Before transformation, one sample *t*-test shows that the mid-test scores are significantly higher than pre-test scores (TFC group: $F(1,48) = 20.20$, $p < .01$; PFFC group: $F(1,48) = 10.74$, $p < .01$); and post-test scores are significantly higher than pre-test scores (TFC group post-test $F(1,48) = 5.96$, $p < .05$; PFFC group: $F(1,48) = 5.33$, $p < .05$); no significant difference is found in the score of the mid- and post-tests (TFC group: $F(1,48) = 1.066$, $p > .05$; PFFC group: $F(1,48) = 0.15$, $p > .05$). Given that the level of difficulties from pre-test to post-test is increasing, the results may suggest that both groups show improvement in their learning performance.

After transformation, the data is then analyzed by repeated measures analysis. Mauchly's test of sphericity ($p > .05$) shows that the data does not satisfies the requirement of Repeated Measures analysis, and they are applicable for multivariate analysis. The main effect of tests on different time points is not significant as it should be ($F(df = 2.8) = 0.00$, $p > .05$), the interaction effect between tests on time points and the pedagogical design is significant ($F(df = 2.8) = 6.36$, $p < .01$), and the main effect between the two groups' pedagogical designs is not significant ($F(df = 1) = 0.12$, $p > .05$).

Multivariate analysis of covariance (MANCOVA) test shows that between groups, the T scores of different time points have no significant difference except on the conceptual understanding test ($F(df = 1) = 4.33$, $p < .05$). By controlling the pre-test scores, the difference between mid-test, post-test and conceptual understanding tests is significant($F(df = 1) = 11.13$, $p = .01$; $F(df = 1) = 6.64$, $p < .01$; $F(df = 1) = 13.68$, $p < .01$). Referring to the mean scores of the two groups on each time points, the results indicate that PFFC group performed better than TFC group in the conceptual understanding questions, while TFC group performed better than the PFFC group in the post and mid-tests.

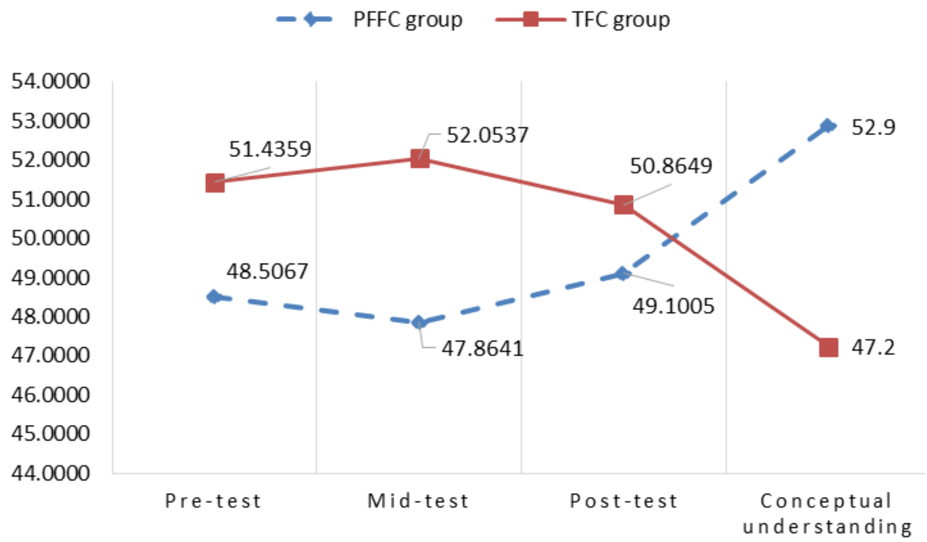


Figure 3. Scores of the four tests in PFFC and TFC groups

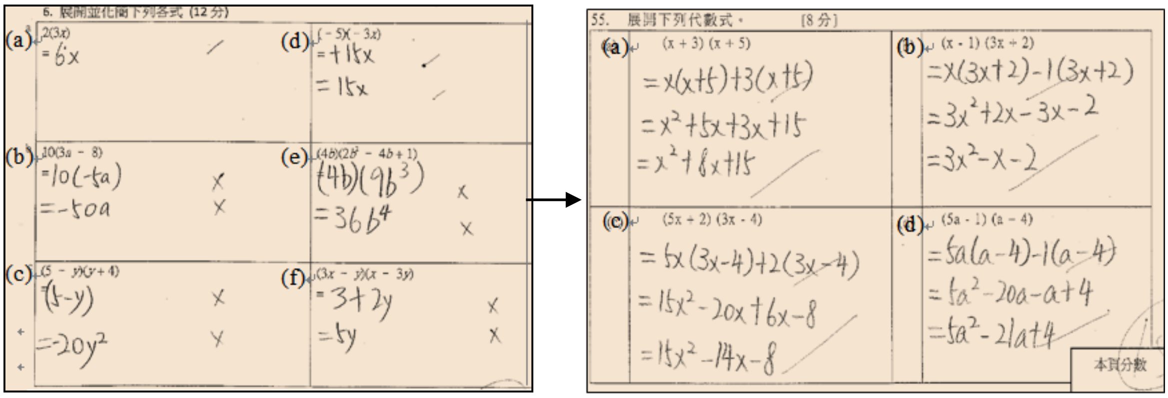
Since all students in TFC group managed to watch the videos before class and previewed the content to be covered in class (refer to Table 2), this meant that the students had the opportunities to acquire procedural knowledge before in-class learning activities; while students in the PFFC group needed to engage and explore the problems in groups to seek solutions first before consolidating what knowledge they had learned, which might put them at a disadvantage compared to the TFC group. This might explain the TFC group' relative higher mean score of mid- and post-tests than that of the PFFC group.

However, students in the PFFC group performed better in conceptualizing the like terms and unlike terms. For example, one question concerned with asking student to discuss the difference between like terms and unlike terms. The best conclusion students in TFC group arrived at was, "I think it can be categorized as numbers and letters"; while a student in the PFFC group mentioned, "If the algebraic expressions and their powers are the same, then they are like terms, if not, they are unlike terms." It is noted that the former conceptualization tended to be too simplistic without giving more concrete ways of distinguishing like terms from unlike ones; while the latter conceptualization was closer to the very definition, i.e., as long as the algebraic expressions and their powers are the same, then they are regarded as like terms.

The results of the three conceptual understanding questions in TFC (with an average correction rate of 52.7%) and PFFC groups (with an average correction rate of 57.6%) are tested by χ^2 test. The results show that χ^2 equals to 58.3 ($p < .01$). This suggests that the learning performance in the two groups is significantly different, and the PFFC group performed better than the TFC group.

An example case of the development of procedural knowledge in each group

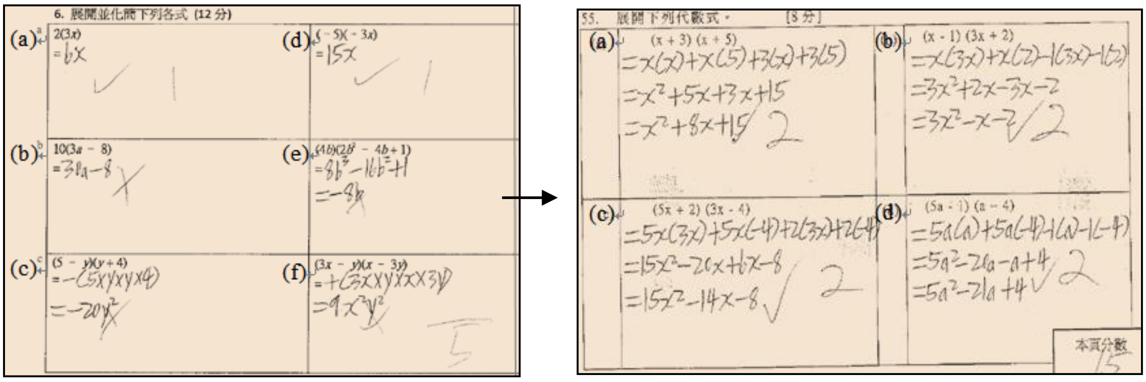
We chose one student from the TFC group and the PFFC group respectively to show their mathematics knowledge advancement, taking a question from the mid-test and a question from the post-test as examples. The students were asked to "expand and simplify the polynomials." Figure 4(a) and (b) show the progress of the student in the TFC group from mid-test to post-test. Figure 4(a) indicates that the student understood the multiplication of unlike terms, but did not understand distributive law of multiplication. Thus, he did not understand the theorem that when a term multiplies two terms, they needed to multiply the two terms with the first term respectively, nor did they understand that only addition and subtraction could happen between like terms; and addition, subtraction, multiplication and division could happen between unlike terms. Take the problem of (b) in Figure 4(a) as an example, which shows that 「3a」 and 「-8」 are not like terms but the student did subtraction between the two. Figure 4(b) shows that after learning, the student not only understood the distributive law of multiplication, but also grasped the knowledge of the definitions of like terms and unlike terms, polynomial addition, subtraction and multiplication, and positive and negative numbers.



(a) (b)

Figure 4. Solutions to expanding and simplifying polynomials in mid- and post-tests by a student in the TFC group

Figures 5 (a) and (b) show the improvement of a student in solving the problems from mid-test to post-test in the PFFC group.



(a) (b)

Figure 5. Solutions to expanding and simplifying polynomials in mid- and post-tests by a student in the PFFC group

Figure 5(a) demonstrates that the student did not understand the distributive law of multiplication. Take the problem (b) as an example. It shows that the student only did multiplication between 「10」 and 「3a」, but ignored 「-8」; the student also worked out the solutions to Polynomial addition and subtraction intuitively. However, Figure 5(b) shows that the student grasped the distributive law of multiplication, in the meantime, understood polynomial four fundamental operations of arithmetic. Moreover, the student had a better and clearer understanding of the concept of the distributive law.

An example case of the development of conceptual knowledge in each group

We choose one conceptual understanding question as an example to show the results in both groups. The conceptual understanding question is as follows:

Given the side length of a square-shaped land is (2a +3) m,

- Determine the perimeter of the square-shaped land in terms of a,
- Determine the area of the square-shaped land in terms of a,
- If there is a triangle-shaped land with area less than that of the square one by $(a^2 + 13a - 7)m^2$, determine the area of the triangle-shaped land in terms of a.

The percentage of correct answers for Parts (a), (b) and (c) are shown in Figure 6 respectively. The χ^2 test shows that overall, PFFC group outperforms TFC group in this conceptual understanding question ($\chi^2(df = 1) = 202.92$, $p < .01$). The results suggest that the "productive failure-based flipped classroom" pedagogical design is more effective than that of the "flipped classroom" in the improving students' conceptual understanding and problem solving skills.

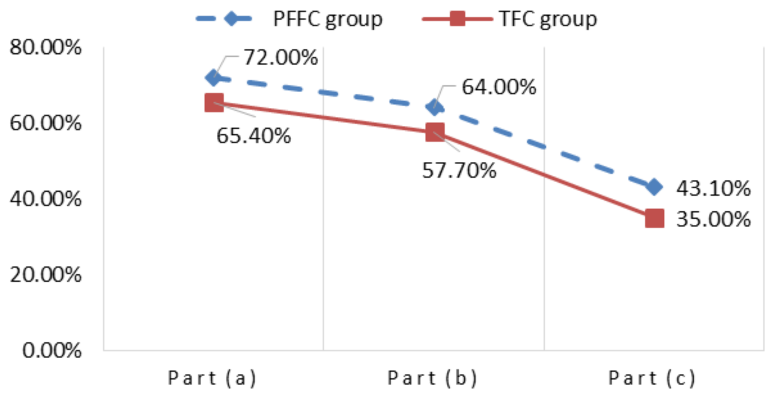


Figure 6. Percentage of correct answers to the conceptual understanding questions in PFFC and TFC groups

Examining further the students' answers, it was found that 4 students in the TFC group skipped answering the questions in Parts (a) and (b). This was not surprising because in general, Secondary 1 students are usually frustrated with mathematics long/conventional questions; in many cases, without fully comprehending the questions, many of them consider themselves not being able to answer the questions, or even give up (Hong Kong Examinations and Assessment Authority, 2013; 2015). However, in the PFFC group, no student gave up. They invested more effort in seeking the solutions. For example, some students from the PFFC group provided the answer $(2a + 3)^2$ m^2 to question Part (b) using exponential notation which was more concise and appropriate than those who answered $(2a + 3)$ $(2a + 3)$ m^2 in the TFC group.

Relationship between video-watching behaviors and students' learning performance

In order to understand whether students' video-watching behaviors influenced students' learning performance, one-way ANOVA test was conducted. The results show that there is no significant effect of watching video times with the results of pre- mid- post- tests ($p > .05$).

Interview results

This section reports the results of focus group discussions in both TFC and PFFC groups. Regard Question 1 (Can you describe the learning activities in learning Polynomials?) and Question 2 (How do you find the learning activities?), both groups could clearly describe the pedagogical activities in their classes and expressed their positive attitude toward the pedagogical approaches. As for why they like the approach, students in the TFC group reported that the approach allowed them to consult teachers and ask help from peers in class when they encountered difficulties. They also deemed that the learning activities were interesting which was quite different from the traditional class, where the teacher lectured in class and students did homework at home. Apart from it, they could watch the videos as many times as they needed if they did not understand the learning content. Nevertheless, the most appreciated feature of the approach by the students was that they could do homework in class. One student reported, "In the past, when I came across difficulties in doing my homework at home, I had no one to consult with. Now I can do homework in class and seek help from others if I have problems. In addition, as I need to spend time watching video clips at home, which reduces the time spent on playing online games as I did before."

While, the students in the PFFC group appreciated the "productive failure-based flipped classroom" because they were provided the opportunities to explore and plan the methods to solve the problem on their own guided by the pedagogical approach, and share their findings in class before the teacher's instruction. In addition, after their own exploration of the problems, they watched the video clips at home which helped them consolidate what they learned in the inquiry, and left deeper impressions on the misconceptions that they had experienced. A student reported, "I like the pedagogical approach because I have the opportunities to explore and provide solutions first. Even if I make a mistake, I will be able to know why I make the mistake by watching the videos or teacher's facilitation. Thus, I will not make the same mistake again."

As for question 3 (What do you think is most important in your mathematics inquiry process?), students in the TFC group considered teacher's facilitation or peers' help in the course of problem solving in class was most important. For example a student reflected that "when I did my home work at home, I had no one to consult with. Now I can ask my teacher or classmates when I encounter difficulties"; while students in the PFFC group deemed that collaboration was crucial in the complex problem solving process as "a few minds are better than one."

Discussions

This study shows that both TFC and PFFC groups improved their mathematics knowledge and problem solving skills on the topic of "Polynomial", and held positive attitude towards their learning experiences. However, it is noted that compared to TFC group, students in PFFC group gained better conceptual understanding of the knowledge related to "Polynomial"; and achieved higher scores in the solving conceptual understanding questions than their counterparts. In addition, their video-watching behaviors and interview results were also different. We discuss these discrepancies in this section.

"Direct instruction" before or after class - Does it matter?

In this study, the TFC group adopted "traditional flipped classroom" pedagogical design, in which students watched video clips to pre-view the new knowledge before they did active learning in class. This means that students received video instruction before they entered into the classroom. While, the PFFC group adopted "productive failure-based flipped classroom" pedagogical design, in which students were engaged in exploring, planning and solving problems first before receiving video instruction for consolidation. Does it matter where to put the video instruction in the pedagogical design?

To delve deep into the pedagogical design, it was found that although both TFC and PFFC groups watched the same video clip, the purposes were different: the "traditional flipped classroom" pedagogical design in this phase did not focus on generating correct solutions in the initial learning stage, but focused on acquisition of basic knowledge of the topic before problem solving (Charles-Ogan & Williams, 2015; Muir & Geiger, 2015); on the contrary, the "productive failure-based flipped classroom" pedagogical design in the "video watching" phase focused on consolidating the concept that students learned in their process of problem solving (Kapur, 2014a; Kapur 2014b). The nature of the learning was divergent: with the former centered on understanding knowledge, and the latter centered on development of conceptual knowledge and knowledge transfer (Kapur, 2016).

The results of the student learning performance show that both groups improved their learning in the mid- and post-tests. However, students in the PFFC group appeared to have better understanding of the concepts than their counterparts. In addition, the results of the conceptual understanding tests show that students in the PFFC group significantly outperformed their counterparts which echoed the research findings in Kapur's study (2011). They tended to be more confident and willing to face the challenging questions and strive for optimal ways to solve the problems than the TFC group. This indicates that the "productive failure-based flipped classroom" pedagogical design is conducive to cultivate students' problem solving skills and enhance conceptual understanding. Further, the students in PFFC group watched the video clips significantly fewer times than their counter parts. This might be due to the fact that students in the PFFC group watched the video clips after their inquiry into the problem, and had better or some understanding of the concept, thus made sense of the concept presented in the video clip by just watching it once.

The results of this study imply that it really matters to students' learning process as for where to put the instructional video clips in the pedagogical design. To understand the nature of students' prior knowledge is a crucial element in the pedagogical design from a constructivist perspective (diSessa, Hammer, Sherin, & Kolpakowski, 1991). However, in "traditional flipped classroom," the students' prior knowledge may not be elicited by watching the instructional video clips solely; while, delaying instructions in "productive failure-based flipped classroom" offers students opportunities to leverage their prior knowledge and the new knowledge under investigation to generate multiple methods for solving a problem (Kapur, 2011).

"In-class learning activities" of the Pedagogical design – Do they matter?

The in-class learning activities designed in the "traditional flipped classroom" and "productive failure-based flipped classroom" were varied. The former one focused on doing exercises and solving students' own learning problems at their own pace (e.g., Jungić et al., 2015; Lai & Hwang, 2016); the later one laid emphasis on encouraging students to explore, discuss and work out solutions on their own with the pedagogical guidance (e.g., Westermann & Rummel, 2012), no matter whether their solutions were correct or not (Kapur et al., 2006).

In the in-class activities of the "traditional flipped classroom," it was noted that students were expected to apply the knowledge acquired from video-watching activity before the class to engaging and discussing more difficult problem solving tasks to cater for their learning needs (Herreid & Schiller, 2013; Muir & Geiger, 2015); while, in the in-class activities of the "productive failure-based flipped classroom," students were engaged in inquiring into the problems and seeking solutions built on their prior knowledge. Although they might encounter impasse or temporary failures, they were able to overcome these difficulties in the process of exploring and analyzing problems (Granberg, 2016) as well as through teacher facilitation or peer interactions in class. They could also assembly and organize the polynomial concept related features after class through watching the instructional video clips. Kapur (2011) posits that the teacher's role is critical for students' learning: students learn when the teacher provides assistance just at the zone of proximal development (Bruner, 1986). Even delaying help may be more productive in developing their epistemic and problem solving skills (Bielaczyc & Kapur, 2010; Kapur, 2011). However, students in the in-class activities in "traditional flipped classroom" might be deprived of the opportunities to activate their prior knowledge by direct video instruction before entering the in-class activities, which were likely to hinder their development of problem solving skills and knowledge transfer in the in-class activities (Kapur, 2016). Thus, the learning activities in the pedagogical design in class do matter to students' learning.

Limitations

The results of this study cannot be generalized due to a small number of participants involved, and a short study period. In addition, the individual data was aggregated at the group level to address the efficacy of a group as a whole; but the aggregated data might not be able to predict individual learning (Cress, 2008). The results might also be influenced by the two different teachers taking different classes. Moreover, some concerns have not been resolved in this study. For example, in terms of using tablets or desktop computers to watch the video clips, the number of students in the PFFC group was significantly higher than those in the TFC group. Does this difference influence their learning performance? If yes, how? Do we need to prepare different video learning content in "traditional flipped classroom" and "productive failure-based flipped classroom" owning to the different pedagogical designs? How can we better trace and examine the students' problem solving process and outcomes, and learn from mistakes (Kapur & Bielaczyc, 2012) in "productive failure-based flipped classroom"? These are the questions that deserve to be addressed in future research studies.

Conclusion

This paper reports on a quasi-experimental study of investigating the impact of two different pedagogical designs in flipped classroom on students' knowledge advancement and development of conceptual understanding and problem solving skills: the TFC group in the "traditional flipped classroom" condition and the PFFC group in the "productive failure" condition. It was found that although both pedagogical designs could help improve students' procedural knowledge, the PFFC group significantly exceled the TFC group in terms of conceptual understanding and problem solving skills related to "polynomial." The "productive failure-based flipped classroom" pedagogical design with the transformed strategies of "Productive Failure" and "Flipped classroom" was inspiring for both teachers and students. For teachers, it transforms what used to be a more unidirectional way of teaching in classroom setting into one that places more emphasis on student-centered discovering and inquiring (Krajcik et al., 2000; Marshall, & Horton, 2011). At the same time it "flips" the general idea of having students view instructional videos to learn the content of knowledge at home before class in "flipped classroom" to having students question, think and discover by themselves before watching instructional videos after class so as to consolidate what is learned. This pedagogical approach encourages students to actively question the unknown and find solutions on their own (Kapur, 2014a; Kapur 2014b). It also extends the learning process outside class that allows students to have more time for thinking and discovering in class, thereby promoting their problem solving skills. Thus, the "productive failure-based pedagogical design" indeed addressed the twin demands of covering the mathematics curriculum and motivating students to learn (Muir & Geiger, 2015). Throughout the adoption of this pedagogical design, mobile devices like smart phones played an important, supplementary role to help the students reach their learning goals. Whether the screen size and devices may influence students' learning performance deserves further research.

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