Developing Technological Pedagogical Content Knowledge in Technology-Rich Learning Environments: The Affordances of Self-Regulated Learning Theory

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DEDICATION

I dedicate my dissertation to my father Huatian Huang and my mother Xiaohong Huang, who have provided me with their greatest love and support for my growth.

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AUTHOR CONTRIBUTIONS

The dissertation consists of five chapters. I wrote Chapter 1 and 5 independently and Dr. Susanne Lajoie serves as an advisor throughout the process of planning, editing, and revising each aspect of the dissertation. I also wrote Chapter 2 independently. The original version of this chapter was prepared in partial fulfillment of my comprehensive exam. Dr. Lajoie, Dr. Adam Dube, and Dr. Eric Poitras provided feedback in their roles as members of the comprehensive exam evaluation committee. I wrote the first empirical manuscript presented in the dissertation (Chapter 3). The version compiled in the dissertation is the version published in the British Journal of Educational Technology. Shan Li, Dr. Poitras, and Dr. Lajoie co-authored and provided feedback. I wrote the second empirical manuscript of the dissertation (Chapter 4) independently, and Dr. Lajoie provided feedback on some aspects of the research. This manuscript is the version published in Computers and Education. The contributions of myself and my co-authors are described in more detail below.

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Chapter 2

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Contributions

I was responsible for writing the entire manuscript. Dr. Lajoie, Dr. Adam Dube, and Dr. Eric Poitras provided feedback on the draft.

Chapter 3

Citation

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Contributions

I was responsible for conceptualizing research questions and hypotheses, analyzing data, writing the original draft, and revising the manuscript according to reviewers' comments. Shan Li supported data analysis. Dr. Poitras provided the data collected by him in 2015. Dr. Lajoie supervised the research and modified the writing. All co-authors provided feedback on the original draft and the revision.

Chapter 4

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Contributions

I was responsible for conceptualizing research questions and hypotheses, collecting and analyzing data, writing the original draft in its entirety, and revising the manuscript according to reviewers' comments. Dr. Susanne Lajoie provided feedback on the original draft and the revision.

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ABSTRACT

Teachers need to acquire technological pedagogical content knowledge (TPACK), professional knowledge that is needed for the effective use of technology in teaching. TPACK requires understanding the affordances of technologies and aligning the affordances with the features of subject matter, pedagogical strategies, students, and learning contexts. However, teachers often report difficulty developing TPACK since they fail to monitor and control certain aspects of their learning to accomplish a technology-infused instructional task. Literature reveals that fostering self-regulated learning (SRL) abilities can help individuals acquire complex knowledge and address difficult problems. Accordingly, this research project aims to promote teachers' TPACK development by enhancing their SRL abilities in designing a technology-infused lesson. A technology-rich learning environment (TRE) - nBrowser is adopted to facilitate lesson design activities and foster teachers' SRL engagement. This dissertation presents a conceptual model that justifies the role of teachers' SRL in the domain of TPACK. It also provides empirical foundations exhibiting how teachers' SRL affects learning about TPACK. The findings have implications for how teacher educators use SRL models to foster TPACK acquisitions as well as the broader impacts for future research that can design TREs to scaffold SRL skills in TPACK contexts.

RÉSUMÉ

Les enseignants doivent acquérir des connaissances sur le contenu pédagogique technologique (TPACK), des connaissances professionnelles nécessaires à l'utilisation efficace de la technologie en classe. TPACK nécessite de comprendre les avantages des technologies et de les aligner sur les caractéristiques de la matière, les stratégies pédagogiques, les étudiants et les contextes d'apprentissage. Cependant, les enseignants signalent souvent des difficultés à développer TPACK car ils ne parviennent pas à suivre et à contrôler certains aspects de leur apprentissage pour accomplir une tâche pédagogique. La littérature révèle que favoriser les capacités d'apprentissage autorégulé (SRL) peut aider les individus à acquérir des connaissances complexes et à résoudre des problèmes difficiles. En conséquence, ce projet de recherche vise à promouvoir le développement TPACK des enseignants en améliorant leurs capacités SRL dans la conception d'une leçon imprégnée de technologie. Un environnement d'apprentissage riche en technologies (TRE) - nBrowser est adopté pour faciliter les activités de conception de cours et favoriser l'engagement des enseignants dans le SRL. Cette thèse présente un modèle conceptuel qui justifie le rôle des SRL des enseignants dans le domaine du TPACK. EIle fournit également des bases empiriques montrant comment la SRL des enseignants affecte l'apprentissage de TPACK. Les résultats ont des implications sur la façon dont les formateurs d'enseignants utilisent les modèles SRL pour favoriser les acquisitions TPACK ainsi que les impacts plus larges pour les recherches futures qui peuvent concevoir des TRE pour échafauder les compétences SRL dans des contextes TPACK.

CHAPTER 1

Introduction

Technology, in the field of education, often refers to tools designed based on learning theories that are used to facilitate learning and improve performance (Lowenthal & Wilson, 2010; Richey, 2008). These types of technology rich learning environments can support, transform and extend learning for a specific instructional situation (Lajoie & Azevedo, 2006). Recent years have demonstrated a huge growth in the use of technology in the classroom that include the emergence of more advanced tools that rely on the Internet and artificial intelligent techniques. Educational practitioners are adopting advanced technologies to create student-centered learning environments that embed artificial intelligence algorithms to monitor and adapt to students needs, helping students make deep inquiries into complex tasks and achieve higher learning outcomes. For example, complex video games are used to teach children scientific topics (e.g., Taub et al., 2018); simulations are designed to help medical students diagnose diseases (e.g., Lajoie, 2015), and; virtual learning spaces allow students to consult online information and interact through asynchronous discussions (Kazemitabar et al., 2016). There is no doubt that technology plays a vibrant role in 21st-century education (Hashim, 2018; Martin et al., 2011; Selwyn, 2012; Selwyn et al., 2020), especially during the COVID pandemic where remote education has become a necessity for many individuals. As breakthroughs in technology continue so too will the affordances that technology can present to educators and policymakers in the future.

However, even with these technological advances teachers are not necessarily embracing these new tools (Halverson and Collins, 2018). The International Society for Technology in Education (ISTE) emphasizes that teachers need to integrate technology into their teaching to help students obtain information in a timely manner, to analyze and synthesize information, and present it professionally (Crompton, 2017). As the need for technology integration increases researchers have paid more attention to teachers' abilities to use technology effectively in the classroom. Pierson (2001) suggested that teachers must learn to master their understanding of technology use to become expert teachers. She found that teachers with exemplary technology-usage skills spend a considerable amount of time working with technologies, value their functions, and create more complex instructional activities that are student-centered (Pierson, 2001). As she stated, “a teacher who effectively integrates technology would be able to draw on extensive content knowledge and pedagogical knowledge, in combination with technological knowledge” (Pierson, 2001, p. 427). Pierson is the first person who used the term technological pedagogical content knowledge to describe the relations between content, pedagogy, and technology. Mishra and Koehler kept the term in their seminal paper (Koehler & Mishra, 2005) and acronymized it as TPACK[1]. Since then, TPACK has been a key topic in the field of technology education. TPACK denotes the three individual knowledge domains (content, pedagogy, and technology), their inter-relatedness, and the role of student characteristics and external factors play in teachers' technology use (Angeli & Valanides, 2009; Graham, 2011; Mishra & Koehler, 2006; Voogt et al., 2013). Furthermore, TPACK provides methodological instructions to guide teachers on how to transform their understandings of individual domain knowledges into a holistic comprehension of TPACK, assisting them in their teaching practice with technology (Angeli & Valanides, 2009). As such, TPACK serves to conceptualize what

[1] The term technological pedagogical content knowledge was initially acronymized as TPCK. It was changed to TPACK in 2007 (Thompson & Mishra, 2007). To avoid confusion, I use the TPACK in the entire dissertation.

successful technology use is and helps direct technology-related research and practices.

Research on TPACK has made remarkable progress in the past 20 years in terms of formulating theory and assessing TPACK across disciplines with multiple methods. For example, TPACK has been conceptualized as an integrative (Mishra and Koehler, 2006) or a transformative construct (Angeli and Vanalides, 2009), and teachers' TPACK has been assessed using different instruments such as questionnaires and interviews (Koehler et al., 2012; Voogt et al., 2013; Willermark, 2018). Despite this progress, there is room for change. In terms of theory work, neither the integrative or the transformative TPACK perspective addresses the developmental nature of TPACK. The research community needs a coherent conceptualization of TPACK as a complex system. In terms of methodology, self-reporting measurements are often criticized due to the issue of validity and reliability. More objective approaches are needed to generate more fine-grained data for more nuanced interpretations and inferences. Additionally, it is important to research teachers' TPACK development in authentic learning environments. In doing so, researchers can gain insights into how teachers' reasoning is related to their selection and implementation of technologies to present subject topics and assist pedagogical designs. Furthermore, we should consider promoting life-long skills such as self-regulated learning to help teachers learn about new technologies and update their TPACK accordingly.

Consequently, the objective of this dissertation is to addresses the concerns mentioned above. Specifically, when working on the conceptualization of TPACK, I postulate that TPACK, as a knowledge construct, encompasses a declarative form and a procedural representation. The former relates to what components are involved in the TPACK model and the later illustrates how teachers apply knowledge into practice. I also emphasize the critical role of teachers' self-regulated learning (SRL, Zimmerman, 2002) in learning about TPACK. Educational psychologists define SRL as an active learning process wherein learners use a wide range of cognitive strategies to acquire topics and metacognitive strategies to monitor and control the entire process (Winne & Hadwin, 1998). SRL is pivotal for learning complex subjects or topics like science (Azevedo et al., 2004), medicine (Lajoie et al., 2015) or history (Greene et al., 2010). Students with successful SRL are found to go beyond rote learning and have deep understandings of complex knowledge systems (Greene et al., 2009). As such, TPACK researchers postulate that SRL is significant when teachers engage in TPACK-relevant tasks that challenge them (Kramarski & Michalsky, 2009; Poitras et al., 2017). Previous research shows that SRL allows teachers to critically think of the affordances of technologies and to make inferences about the relations between technology, content, and pedagogy. In this dissertation I will study teachers acquisition of TPACK with the nBrowser. The nBrowser is a technology-rich learning environment (TRE, Lajoie & Azevedo, 2006) that is guided by learning theories and has instructional functions to provide multiple representations of materials and feedback to learners' achievements (Lajoie & Poitras, 2017). Designed to help teachers integrate technology into their lesson planning. nBrowser can capture teachers SRL to determine the relationship between SRL and technology integration while teachers are learning to integrate technology.

There have been several empirical studies into the role of teachers' SRL in TPACK. For example, Kramarski & Michalsky (2009) found preservice teachers who were supported by SRL prompts outperformed those without SRL scaffolds. Similarly, the results of Poitras et al.'s (2018) study revealed a stronger relationship between teachers' information seeking efficiency and their self-regulatory efforts in the context of SRL-scaffolded TPACK development. The previous research adds significant support to understanding TPACK. This dissertation will further our understanding of the research focus by capturing teachers' SRL to determine the relationship between SRL and technology integration. Hence, we target the following two research questions with empirical data: (1) how do teachers' SRL abilities influence their TPACK development? (2) do teachers show different SRL processes when they show different TPACK competencies? Answers to these questions are addressed in the following three manuscripts in this dissertation to provide a better understanding of developing TPACK in TREs. Manuscript 1 is presented in Chapter 2 and it is a conceptual paper that presents 3 highlights: (a) it conceptualizes TPACK as procedural knowledge; (b) proposes a process-oriented TPACK (CoTMEC^{+}) model that articulates the role of SRL in TPACK development, and (c) discusses the potential of alternative approaches to measuring TPACK in TREs.

Manuscript 2 is presented in Chapter 3 and presents findings obtained from an empirical study that adopts text analysis to identify the teachers' self-regulatory activities (i.e., cognitive and metacognitive events) in learning TPACK through lesson design practice and examines the influences of teachers' SRL in their TPACK acquisition and performance.

Manuscript 3 is presented in Chapter 4 and reports on a second empirical study that investigates teachers' SRL in the context of TPACK development. In this study, teachers' SRL is retrieved and captured from computer trace data and modeled via process analysis. Findings indicate that diverse SRL patterns are associated with different levels of TPACK achievements.

Chapter 5 concludes the lines of research presented in this dissertation, summarizing the findings, highlighting its contribution to the advancement of knowledge in SRL and TPACK, discussing the limitations and future directions for developing TPACK in computer-based learning environments.

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CHAPTER 2

Epistemological and Methodological Reconsideration of Technological Pedagogical Content Knowledge in Technology-Rich Environments

Huang, L., Lajoie, S. P. (ready for submission). Epistemological and Methodological Reconsideration of Technological Pedagogical Content Knowledge in Technology-Rich Environments. *Metacognition and Learning*.

Abstract

Teachers' technological pedagogical content knowledge (TPACK) is critical for their adoption of technology tools in teaching to make subject matter more accessible and easier to understand for learners. However, more work needs to be done to develop the framework towards a solid theory. In this paper, we critically reviewed the current perspectives to understand the nature and function of TPACK. Based on the review, I proposed a new conceptualization of TPACK. It is assumed as a blend of the declarative knowledge indicating the teachers' mastery of TPACK and the procedural knowledge indicating that teachers apply TPACK to accomplish technology-integrated tasks. Drawing on self-regulated learning theory, I created the CoTMEC$^+$ model highlighting the steps and transforming processes involved in TPACK learning. In terms of methodology, the second part of the paper provides a novel approach that measures and scaffolds TPACK simultaneously. The proposal of the new approach leads to the discussion of developing TPACK in technology-rich environments that hold the potential to asses teachers' TPACK learning trajectories with traces and provide timely feedback.

Epistemological and Methodological Reconsideration of Technological Pedagogical Content Knowledge in Technology-Rich Environments

Although we are in the midst of a digital revolution that can impact learning the advantages of this revolution do not appear to have found their way into our educational institutions (Collins & Halverson, 2009). There has been a great deal of discussion about the potential technology has to make the subject matter more accessible and easier to understand for learners. However, teachers use of technology tools requires examination. The early requirements for teachers' technology competencies include mastering basic technological skills such as hardware knowledge (e.g., connecting to the overhead projector) and software application (e.g., word processing). Teachers are assumed to use technology in a proficient venue in their instruction (Wiebe & Taylor, 1997). However, there is little research on supporting teachers as they learn to use technology to facilitate student-centered learning which is ill-structured in nature. Researchers seek to develop a better framework for understanding the development of teachers knowledge as it pertains to their use of technologies to facilitate student learning effectively (Angeli & Valanides, 2009; Draper et al., 2004; Graham et al., 2004; Graham, 2011; Mishra & Koehler, 2008). To this end, technological pedagogical content knowledge (TPACK) is defined as the professional knowledge needed to understand effective and highly skilled teaching with technology (Koehler et al., 2013; Koehler & Mishra, 2009). TPACK is described as situated, complex, multifaceted, integrative, and transformative and is construct studied in both research and practices related to the use of technology in education (Angeli & Valanides, 2009; Chai et al., 2012; Harris et al., 2010; Manfra & Hammond, 2008; Mishra & Koehler, 2008).

As research on TPACK has increased research findings have indicated that teachers have difficulties attaining TPACK (Angeli & Valanides, 2005; Kohen & Kramarski, 2012; Poitras et al., 2017). One explanation is that teachers are less competent in self-regulated learning (SRL) abilities that account for teachers' active management of their own learning process by evaluating and controlling their efforts to acquire TPACK and apply it in practice (Kohen & Kramarski, 2012; Poitras et al., 2017). The literature has shown that teachers who are proficient at SRL are more able to succeed in their own learning and optimize their students' abilities to regulate their learning (Kramarski & Kohen, 2017). However, very few studies have examined the role of teachers' SRL in TPACK acquisition. To examine this relationship more carefully, we propose a model that provides new insights into what TPACK is and clarifies how teachers' SRL can influence their learning about TPACK. Based on the model, suggestions are made for innovative methods that measure TPACK in the context of a technology-rich environments (TREs) that can assess and scaffold teachers' SRL as they acquire TPACK. Implications for integrating TREs into the TPACK training curriculum are presented along with the need to test the proposed theoretical model with empirical studies.

TPACK Conceptualizations

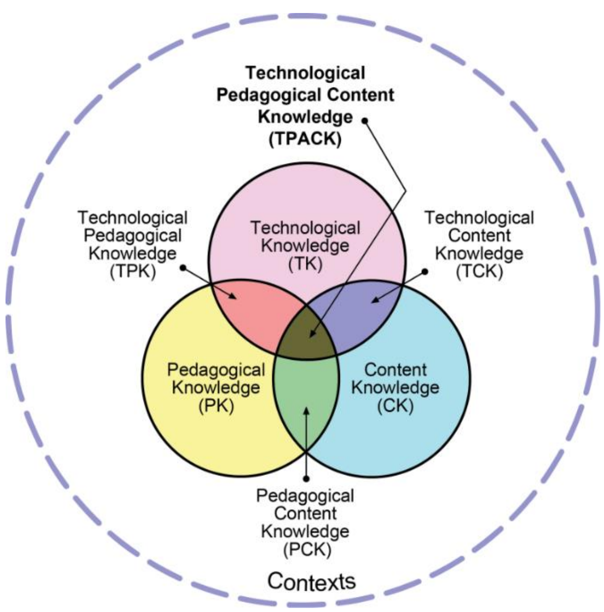
The aim of reviewing conceptual views on TPACK is to address the key features of each view and examine how they answer the questions as to what TPACK is. Regarding the scope of review, we focus on two prominent theoretical views of TPACK, namely, the integrative view represented by the Mishra and Koehler' TPACK framework (Koehler & Mishra, 2005) and the transformative view represented by the ICT-TPCK model (Angeli & Valanides, 2009). Other voices suggest the increase in the number of components to reflect the complexity of technology integration (e.g., Chai et al., 2013; Porras-Hernández & Salinas-Amescua, 2013) or the decrease in components to have the framework concise (e.g., Brantley-Dias & Ertmer, 2013). These discussions are not included in this review since they are seen as modifications of the two dominant views rather than new conceptual perspectives. This section will present the two TPACK views, followed by a critical evaluation of each conceptualization.

The Integrative View

To our knowledge, Graham (2011) first used the two terms - integrative vs. transformative (Gess-Newsome, 2002) to distinguish the current perspectives on TPACK. The integrative view states that TPACK consists of several distinct contributing knowledge domains. Mishra and Koehler (2008, 2006) were credited as introducing the TPACK framework (Figure 1) which represents the integrative views. This framework includes three primary components. Content knowledge (CK) refers to the topics and concepts relating to a given subject indicated in the curriculum, like poetry in literacy, functions in mathematics. Pedagogical knowledge (PK) describes the general knowledge and strategies of instruction, assessment, and student management. Technological knowledge (TK) denotes teachers’ skills and abilities to use hardware such as technologies such as computers, overhead projectors, and software like Microsoft applications, digital videos. Beyond those primary factors, the TPACK model is characterized by additional compounding elements. Succinctly, pedagogical content knowledge (PCK) indicates the methods of teaching specific subject matter. Technological content knowledge (TCK) indicates the ways teachers adopt technologies for content presentation. For example, a geography teacher uses simulations in presenting the wind scale. Similarly, combining TK and PK yields technological pedagogical knowledge (TPK) that describes the ways teachers leverage technologies to teach and manage students, such as assigning homework through a learning management system. In the center of the Venn graph is TPACK, defined as knowledge of adopting different types of technology to teach subject matter with reference to pedagogy.

Figure 1

The TPACK Framework (Mishra & Koehler, 2006, attributed as http://tpack.org)



In addition to Mishra and Koehler's general framework, other theoretical papers have influenced the TPACK conceptualization. As early as 2001, Pierson used the term technological pedagogical content knowledge to illustrate the intersection of content, pedagogy, and technology (Pierson, 2001). However, she did not provide concrete justifications concerning the term except to emphasize that teachers should be able to align extensive knowledge of subject contents and pedagogy with an understanding of specific features of technologies for the sake of good technology integration (Pierson, 2001). Niess (2005) used the technology-enhanced PCK (they acronymized it as TPCK) to describe their understanding of TPACK. According to Niess (2005), TPCK is an integration of knowledge of technology, subject matter and the knowledge of teaching and learning to supports teaching with technology. Cox and Graham (2009) created an elaborated model of TPACK to analyze and depict teacher knowledge. They based their model based on Mishra and Koehler's TPACK framework and clarified the definitions and boundaries of individual contributing knowledge bases, contributing to a conceptual understanding of TPACK.

Taken together, research has repeatedly reaffirmed the assumption that TPACK is the combination of several independent subdomain elements (Cox & Graham, 2009; Mishra & Koehler, 2006; Niess, 2005; Pierson, 2001). All researchers who advocate the integrative view acknowledge the complex nature of TPACK due to the intricate relations between each other. Mishra and Koehler (2009) articulated this by saying,

> TPACK is the basis of good teaching with technology and requires an understanding of the representation of concepts using technologies; pedagogical techniques that use technologies in constructive ways to teach content; knowledge of what makes concepts difficult or easy to learn and how technology can help redress some of the problems that students face; knowledge of students' prior knowledge and theories of epistemology; and knowledge of how technologies can be used to build on existing knowledge and to develop new epistemologies or strengthen old ones. (pp. 1028–1029).

The general framework of TPACK by Mishra and Koehler has prevailed and makes a significant impact on subsequent research. Teacher education and professional development programs draw on this framework as the major theoretical basis to design training schemes supporting teachers' acquisition of all three of these knowledge domains in an integrated manner (Koehler et al., 2017). Although this framework presents a contribution, the general framework was criticized for misrepresenting TPACK as a simple accumulation of individual components. Learning each component domain does not automatically produce TPACK. Therefore, researchers proposed the transformative model, an alternative perspective to theorize TPACK.

The Transformative View

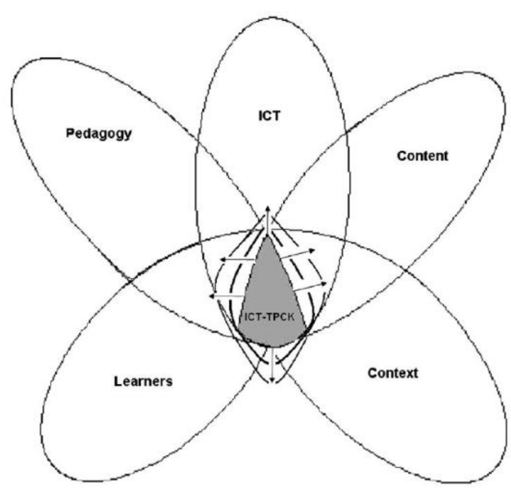
While the integrative views outline the knowledge bases essential for TPACK development and hold potential for wide applications across contexts, the framework fails to clarify the underlying degree of complexity in acquiring the basic contributing knowledge, namely content, pedagogical and technological knowledge (Angeli & Valanides, 2009; Graham, 2011). Angeli and Valanides (2009) address this issue by proposing the ICT-TPCK model (Figure 2). Their model limits the scope of technology to information and communication technology. TPACK[2], according to Angeli, is defined as "a unique body of knowledge about tools and their pedagogical affordances, pedagogy, content, learners, and context are synthesized into an understanding of how particular topics that are difficult to be understood by learners, or difficult to be represented by teachers, can be transformed and taught more effectively with ICT, in ways that signify

[2] Angeli and Valanides kept the acronym TPCK in their work.

the added value of technology" (Angeli & Valanides, 2009, pp. 158–159). In addition to teachers' subject knowledge, pedagogical knowledge, technology, the model integrates two new knowledge bases, that is, understanding of students and perceptions about teaching contexts. Angeli and Valanides (2009) found from their empirical studies (e.g., Valanides & Angeli, 2008) that teachers adapted their technology use to student learning-related difficulties as well as intricacies of the learning environments. The ICT-TPCK model is related to the transformation of these categories of knowledge domains. However, different from the integrative views, Angeli and Valanides (2009) do not denote a specific compounding knowledge in their model. Rather, they attribute different combinations of any elementary knowledge to teachers' TPACK. For example, when a teacher presents subject matter with ICT tools, they produce a certain level of TPACK. In doing so, TPACK can develop through teachers continuously including more factors into technology adoption. Graham (2011) defines such conceptualization as transformative since TPACK herein is not the accumulation of componential elements.

Figure 2

ICT-TPCK Model (Angeli & Valanides, 2009, p. 159)



Another line of work that falls within the transformative category was conducted by Krauskopf, Zahn, and Hesse (2015), who proposed the mental model view of TPACK. They articulated how individual basic knowledge bases (i.e., content, pedagogy, and technology) are transformed to TPACK with the focus on the underlying cognitive processes characterizing the transformation. In general, Krauskopf et al. (2015) assume two levels of transformation during the process of TPACK development. The initial stage is related to the transformation of basic sub-domains to intersecting sub-domains (e.g., TCK), and the second stage occurs when teachers are using TPACK as meta-knowledge to become aware of "the demands of the teaching task at hand, the teachers' knowledge in the sub-domains, and the contextual constraints" (Krauskopf et al., 2015, p. 56). Krauskopf et al. (2015) assume that TPACK is based on teachers' mental model representations of sub-domains and their interrelations that are constructed based on their prior knowledge and beliefs. For example, the transformation of technology and pedagogy can be understood as the process wherein teachers build on a mental model of the functions of a given technological tool and relate these functions with their impact on organizing instructions and managing students. The contribution of the mental model view of TPACK is threefold. First, it clarifies the boundaries of each individual knowledge domain and elaborates on how TPACK grows from the simple sub-domains to complicated intersecting ones. Second, it confirms TPACK as coherent knowledge but credits the individual sub-domains as an essential prerequisite for TPACK. Third, conceptualizing TPACK as meta-knowledge allows teachers to think and reflect on the quality of technology use in relation to different transforming situations and to calibrate their long-term understanding of TPACK accordingly.

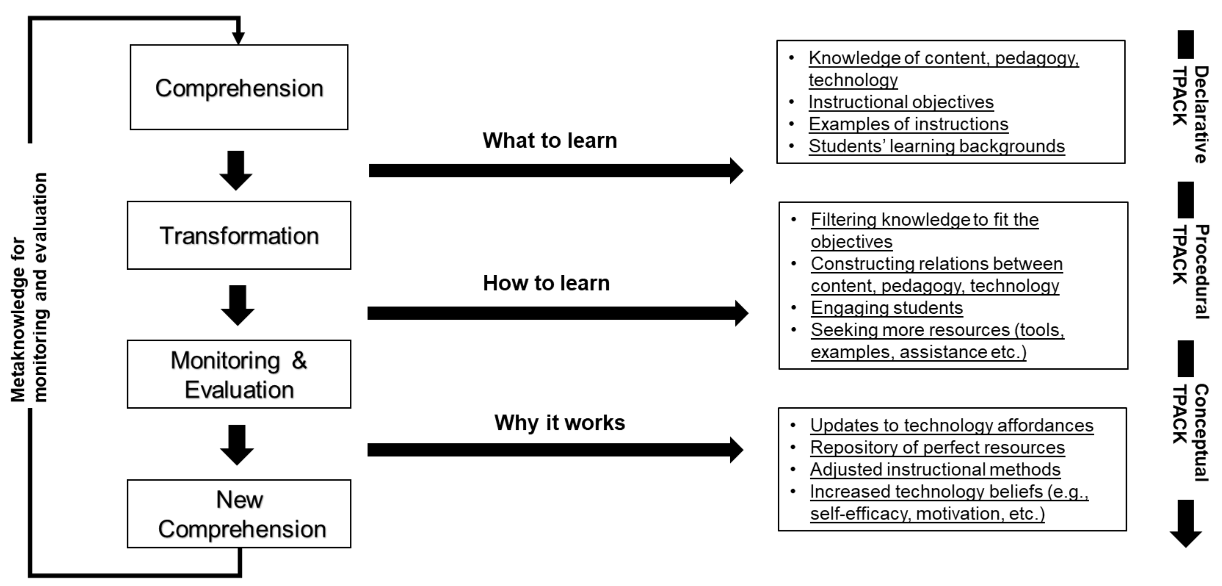
The Next Step in Conceptualizing TPACK

The review of the two predominant views on TPACK demonstrates that content, pedagogy, and technology are three essential components involved in TPACK, and fostering sophisticated TPACK is highly related to contextual factors like students' needs and teaching contexts (Angeli & Valanides, 2009; Krauskopf et al., 2015; Rosenberg & Koehler, 2015; Voogt et al., 2013). Although not explicitly stated the integrative view may be considered as a declarative representation of TPACK, whereas the transformative view is more procedural. Declarative knowledge refers to what individuals are supposed to master while learning about topics, which includes a variety of representations from the statements of definitions to the elaborations of processes (Winne, 2011). Procedural knowledge, on the other hand, refers to the ways of applying declarative knowledge to accomplish tasks, which can be identified as an IF-THEN-ELSE production system applied to perform a task (Winne, 2011). Based on this understanding, we propose a new conceptualization of TPACK that blends the declarative knowledge indicating the teachers' mastery of TPACK and the procedural knowledge indicating that teachers apply TPACK to accomplish technology-integrated tasks. For example, if instructors want to organize collaborative discussions in an online course, they first ought to clearly understand the general affordances and constraints of the online instructional platform and analyze what features of the online platform could support their pedagogical design (i.e., collaboration). Subsequently, the instructors organize their instruction step by step and implements it in their teaching. In this example the instructors' TPACK is represented by their understandings of the online contexts (TK), the knowledge of collaboration (CK), and the plan of organizing online collaborative discussion strategies (TPK). These bodies of knowledge belong to the declarative category. When the instructor implements the plans for teaching, they are developing TPACK as procedural knowledge.

To align with this new conceptualization, we create the CoTMEC$^+$ (Comprehension – Transformation – Monitoring & Evaluation – New Comprehension) view of TPACK which is a stepwise model (Figure 3) which indicates the essential stages underlying TPACK development. Each stage is interdependent and the success in the previous stage leads to the subsequent one.

Figure 3

The Four-Stage CoTMEC$^+$ Model



Stage 1: COMPREHENDING the Instruction Task

Comprehension, in the TPACK context, refers to analyzing the factors that affect the completion of the task, such as reviewing which topics and concepts will be taught, knowledge of pedagogical strategies, available technologies and other resources, students learning styles and so forth. Teachers' comprehension enables them to examine the subject matter topic and decide on the specific focus of the topic and the possibilities of student difficulties of learning such a topic. Teachers will retrieve pedagogical strategies they have already learned or used from previous experience. Teachers can also activate prior knowledge regarding what technologies might work in general or in specific topics. Comprehension also involves the survey of students and the external teaching condition. There is a hypothesis that teachers produce more independent knowledge domains like content, pedagogy, and technology, even though they might consider the interrelationships among different domains. TPACK, in this stage, is assumed as the declarative format.

Stage 2: TRANSFORMING Knowledge into Forms that can be Taught

Following comprehension, the teacher transforms their insights into the task and the given context into the forms that can be taught and learned easily. In this stage, the teacher often mentally makes a list of ways the subject matter can be represented. For example, a math teacher may use the image of pizza as an analogy to explain the concept of fractions. A foreign language teacher could draw on digital pictures to create the relation between a vocabulary and its abstract meaning. Instructional strategies are also of concern in this stage. A teacher can ask students to answer their questions in public or in the interactive virtual chat room anonymously. There is no fixed approach for teachers to follow. Rather, teachers are encouraged to use multiple forms of representations (Shulman, 1986). The success of the transformation stage can be attributed to the acquisition of PCK, TCK, TPK, which describes the complexity of technology integration. As emphasized (Abbitt, 2011; Angeli & Valanides, 2009; Cox & Graham, 2009; Harris et al., 2010; Koehler et al., 2014; Krauskopf et al., 2015), the compounding knowledge bases justify how teachers construct the interrelations between content, pedagogy, and technology. Therefore, the outcome of the second stage is posited to be immature TPACK by which teachers explain their technology use.

Stage 3: MONITORING and EVALUATING Transformation

When teachers start monitoring and evaluating the transformation, then TPACK is becoming more procedural. All monitoring and evaluating activities provide teachers information and feedback regarding whether they have a deep mastery of knowledge from all basic categories (i.e., content, pedagogy, technology) and whether they have considered the characteristics of the learners, and available resources from the external contexts. In addition, the processes of monitoring and evaluation are inextricably linked with an adaptation that refers to necessary modifications to align each element to maximize the technology-infused teaching. For instance, the teacher could add or reduce the number of analogies according to students' academic abilities, learning styles, motivation, prior knowledge, and cultural background. This stage can be characterized by using TPACK as meta-knowledge to scrutinize respective aspects and consequences of technology integration. By meta-knowledge, Krauskopf et al. (2015) refer to teachers knowledge of essential contributing knowledge domains (e.g., TK) and strategical alignment of them for accomplishing tasks that highlight the values of technologies. Knowing at the level of meta-knowledge represents a high level of expert knowledge (Krauskopf et al., 2015; Mishra & Koehler, 2008).

Stage 4: Summarizing and Forming New COMPREHENSION

Stage 4 refers to the improved TPACK comprehension teachers gain after they experience the previous three stages. Teachers summarize and reflect on their technology use and generate deep understandings of (1) advantages and disadvantages of technologies in different contexts, (2) technological solutions to teach difficult subjects, (3) technological support in organizing multiple instructional activities (4) technological affordances to enhance student learning. For example, were the contents of the topic and the objectives related?, did I miss material that is important to teaching the topic? was the technology I selected appropriate for the task? was the learning environment well organized? (Kramarski & Michalsky, 2009). The new comprehension is a result of teachers' TPACK acquired through conducting instructional activities. This body of TPACK is considered as a highly contextual and practical complex body of knowledge, which is key to successful technology integration (Angeli & Valanides, 2009). This new comprehension lays the foundation for the next technology-infused instructions, based on what teachers have learned, leading to more advanced technological solutions and pedagogical strategies that could work for more complicated subject topics.

Defining TPACK as knowledge that has both declarative and the procedural forms characterizes the sophisticated property of the TPACK system. Research has shown that learners have difficulties learning complex topics since they often spend more time acquiring declarative knowledge and less effort learning the procedural knowledge critical for understanding how a complex system works (e.g., Azevedo et al., 2004; Chi, 2005; Greene & Azevedo, 2009). In support of our claims, we address the importance of self-regulated learning (SRL) theory to justify how teachers' SRL abilities can enable them to acquire a deep understanding of TPACK and improve their capacities to accomplish technology-integrative teaching.

SRL Mediates TPACK Development

SRL as a Theoretical Basis

Self-regulated learning (SRL) is a vital concept in educational psychology research. It stems from metacognition theory (Flavell, 1979) that describes how students think of their thinking and use metacognitive skills to facilitate learning. Metacognition encompasses the knowledge of cognition that refers to the knowledge of how information is processed, stored as well as retrieved, and the regulation of cognition that refers to strategies for processing cognition in real-world contexts (Brown et al., 1983). The coverage of metacognition is relatively broad. Corno and Mandinach (1983) created the term self-regulated learning and drew on the features of metacognition (Flavell, 1979) to fertilize the integrated theory of regulation in academic domains. The SRL theory denotes a regulatory mechanism for planning, monitoring strategies, evaluating the effectiveness of strategies, and revising in cognitive, motivational, and behavioral dimensions (Dinsmore et al., 2008; Lajoie, 2008; Pintrich, 2000; Winne & Hadwin, 1998; Zimmerman, 2002). Since the work from Corno and Mandinach (1983), research on SRL has continued to develop, and there are several SRL models of high quality in the contemporary literature (Panadero, 2017). Puustinen and Pulkkinen (2001), in their review of SRL models, classified the contemporary SRL models into two categories, namely, the goal-oriented models and the metacognition-driven models. The goal-oriented models like the socio-cognitive perspective of SRL (Zimmerman, 1986) and the general framework for SRL (Pintrich, 2000) argue that SRL is goal-oriented and has the constructive and self-generated feature (Puustinen & Pulkkinen, 2001). The metacognition-driven models, including the information processing perspective of SRL (Winne & Hadwin, 1998) and the metacognitive and affective model of SRL (Efklides, 2008), emphasize that self-regulators metacognitively adapt the use of cognitive tactics and strategies to address tasks (Puustinen & Pulkkinen, 2001). Despite the dichotomous categorization, it is worth mentioning that the two classes are not mutually exclusive. Rather, they do share some common assumptions with respect to learning and regulation.

First, there is an agreement that SRL is a cyclical process proceeding from a preparatory phase to a task completion phase and an adaptation phase, even if the phases vary from one model to another. The preparatory phase's main work is to analyze the tasks to be performed, define clear goals and sub-goals, and plan available strategies. In the stage of task completion, students implement the strategies to address questions that arose in tasks and metacognitively monitor the effectiveness of their strategies. Students will adjust their strategies when they are not powerful enough to address their problem-solving attempts. Subsequently, students evaluate their overall performance, consider the implications, and make adaptations for future learning. What is worth emphasizing is that this is a general description of the phases of SRL. Not all learning follows these phases and all phases do not necessarily proceed in a strict time-order (Azevedo, 2009; Puustinen & Pulkkinen, 2001). There are many metacognitive activities that take place. For example, when students recognize a discrepancy between their performance and the defined goals, some will go back to revise goals and proceed with the following tasks. Others might stick to the goals but adjust learning strategies Different decisions bring the student to the different SRL paths. Such a process will continue until the task is to be completed. More importantly, the nature of weak time-sequence allows researchers to understand how complex SRL processes students have enacted when engaging in learning and making inferences to learning outcomes.

Secondly, contemporary SRL models acknowledge that creating specific goals can foster achievements since the goals incorporate specification that requires a considerable amount of effort to achieve them (Schunk, 1990). A more critical function of setting goals is that the goals can be transformed into standards used for the later monitoring and evaluations. By comparing learning consequences against goals or standards, individuals evaluate their learning outcomes and decide whether to continue the learning or make necessary modifications before stepping into a new task. As such, SRL takes place.

Thirdly, it is assumed that the hub of SRL is a metacognitive monitoring mechanism, which is accompanied by internal feedback (Butler & Winne, 1995; Winne, 2001). Metacognitive monitoring includes self-monitoring and self-evaluations, which enables individuals to identify the differences between the goals or standards and the consequences of learning activities (Winne, 2018). The internal feedback from the monitoring process refers to information about learners' self-assessment of the quality of performance and achievements (Hattie & Timperley, 2007). With internal feedback, learners control or regulate learning by adjusting their goals or strategies for the sake of solving academic tasks (Winne, 2001).

A considerable number of empirical findings have shown that SRL benefits learners and leads them to gain higher performance and better academic achievements (e.g., Azevedo & Cromley, 2004; Bannert et al., 2015; Deekens et al., 2018; Lee et al., 2010). SRL allows learners to be reflective, intentional, and autonomous to address task difficulties, and therefore students who received SRL training and gained stronger self-regulatory abilities tend to outperform those with weaker SRL abilities (Greene & Azevedo, 2009). Additionally, SRL facilitates deep understandings of complicated knowledge. While regulating their learning, students are able to comprehensively understand the intricate system of the knowledge, adaptively use various learning strategies to enhance their understandings, and gain new comprehensions about the knowledge and tasks. As discussed earlier, TPACK is conceptualized as a sophisticated procedural knowledge system. SRL is assumed to have an effect on TPACK acquisition, expanding teachers' understanding of TPACK from what it is to how to apply it to addressing authentic instructional tasks. Therefore, in the following section, the role of SRL in the different stages of TPACK will be described along with how SRL processes may impact TPACK learning.

SRL Processes in CoTMEC$^+$ Model

SRL in Comprehension

Teachers must first comprehend the instructional task prior to working with educational technologies. The SRL model maintains that teachers' understanding of the cognitive conditions and task conditions influence their learning about TPACK.

Cognitive conditions include such things as personal beliefs, motivation factors, domain knowledge, knowledge of the task, and strategies (Winne & Hadwin, 1998). For example, prior knowledge of the subject matter has a significant impact on learning outcomes (Gurlitt & Renkl, 2008; Moos & Azevedo, 2008; Taub & Azevedo, 2018). Learners' epistemic beliefs are closely related to how learners monitor the learning process towards goals (Franco et al., 2012; Muis & Singh, 2018; Trevors et al., 2016). Task conditions are external to the learners and include resources, instructional cues, time, and the local context (Winne, 2018; Winne & Hadwin, 1998). Both cognitive and task conditions influence learning achievements (e.g., Linnenbrink & Pintrich, 2001; Wormington & Linnenbrink-Garcia, 2017). TPACK research raises the awareness of conditional factors, such as teaching experience (e.g., Angeli & Valanides, 2009), previous domain knowledge (e.g., Chai et al., 2012), self-efficacy beliefs (e.g., Semiz & Ince, 2012), and influences of the learning context (e.g., Poitras et al., 2018)

Another significant SRL process that occurs in comprehension is goal construction for task accomplishment. The specificity and complexity of goals depend on teachers' understanding of the tasks. Goals, according to SRL, defines the expected outcomes of any inquiries (Winne & Hadwin, 1998). Goals are associated with standards, multifaceted criteria suggesting optimal qualities of learning performance and outcomes (Winne, 2001). Self-regulated learners are goal-oriented, who create attainable goals and sub-goals to guide learning activities and compare the profiles of performance and outcomes against goals and standards. Therefore, teachers, while learning TPACK, ought to be goal-oriented. The ultimate goal is to leverage technology to optimize student learning. The subgoals perhaps include, but are not limited to, representing content and organizing instruction with technologies. These goals or standards are key to determining the success of any operations the teacher might perform within each stage.

SRL in Transformation

SRL contributes to fostering teachers developing TPACK by means of a wide range of effective strategies. To avoid listing strategies in length, this section will exemplify the SMART construct indicated in the information process model of SRL (Winne, 2001) to explain the transforming process underlying TPACK development. The first strategy construct is searching, which requires retrieving knowledge from long-term memories to determine what might be relevant to the task to be performed (Winne, 2001). For instance, a teacher might recall how they taught the same topic last time or whatever teaching method they have learned from schools or training programs? The search process does not come to an end until they retrieve enough information pertaining to the task at hand. The second strategy of the SMART model is monitoring, a process that enables teachers to compare retrieved information in terms of properties, relevance, and appropriateness. The results of monitoring are a chunk of new information that matches the goals and could be used to address the problems. The next strategy is assembling the information resulted from monitoring to formulate a complete orchestrated knowledge system. TPACK researchers expressed the process as coordinating the different sub-domains (Abbitt, 2011; Cox & Graham, 2009; Harris et al., 2010; Koehler et al., 2014; Krauskopf et al., 2015). Teachers elaborate on the assembling by rehearsal (Craik & Lockhart, 1972; Winne, 2001). Deliberate rehearsal enables teachers to manage how they change their understanding of TPACK with the consideration of contextualized information such as students' demands and contextual constraints (Rosenberg & Koehler, 2015). The rehearsal strategy leads teachers to become an expert at transforming the fragmented TPACK to a coherent concept of teaching with technology. The last strategy is translating. Winne explained the strategy as "a mental capability to use one representational format as a basis for creating another" (Winne, 2001, p. 148). Said differently, the translation strategy is the teachers' ability to transform TPACK gained in a given task to another teaching scenario to create a similar level of TPACK competencies. For example, if a teacher uses digital storytelling to enable visual representations of a poem in a literature class, they may translate this technique to using visual simulations to demonstrate photosynthesis when teaching a science topic. This example can indicate that the teacher has a conceptual understanding of TPACK, that is, knowing the affordance of technology to translate abstract concepts into concrete representations.

In addition to these five strategies teachers may use additional ones to construct their own TPACK. For example, with respect to monitoring, they may use specific strategies such as self-questioning, goal-oriented monitoring and content evaluation (Azevedo et al., 2004, 2012). Moreover, strategy use often occurs in several cycles rather than in a linear manner. Teachers can move back and forth between rehearsing and monitoring before applying another strategy.

SRL in Monitoring and Evaluation

The metacognitive regulatory process is regarded as the core of SRL, involving metacognitive monitoring and metacognitive evaluation. As presented before, the mechanism of the metacognitive process is monitoring-feedback-evaluation. In the

TPACK context, teachers' metacognitive monitoring and evaluating activities are producing the procedural TPACK representation and advancing their TPACK competency towards the expert level. More specifically, self-regulated teachers perform monitoring by comparing technology solutions against the goals or standards developed in the second stage. They check the appropriateness of instructional methods and the plausibility of proposed technologies by considering factors like students' characteristics or available tools. If satisfied with the solutions, teachers then proceed to enact the next steps. But if not satisfied, for example, the desired tools are not conveniently available in a classroom setting, teachers will refine their solutions to look for alternative tools. Such a process iterates several rounds until the solutions match the desired goals or standards.

Monitoring and evaluation are critical for TPACK success, and the metacognitive regulatory process plays a pivotal role in this stage. Given that TPACK is a complex body of knowledge, teachers must consider diverse factors and their influences on TPACK achievements. Kramarski and Michalsky (2009, 2010) reported that support in the metacognitive process through the evaluation phase had a better effect on preservice teachers' TPACK comprehension. Huang and Lajoie (2021) found that teachers with a higher level of TPACK exhibited more effective SRL patterns, in that they performed more metacognitive activities to monitor the design of their TPACK-based lesson plans. In comparison, the teachers in the low TPACK group showed minimal effort in monitoring and evaluation. Metacognitive processes stimulate teachers to progress towards the final solution by modifying their goals and strategies or seeking external assistance if they encounter impasses along the way. TPACK is assumed to more mature if teachers use their meta-conceptual awareness for monitoring and evaluating their knowledge in every sub-domain, task demands, and contextual constraints (Krauskopf et al., 2015). For example, teachers will examine the degree to which they specifically interpret TPACK components with consideration of task and students' features using a mental grading metric indicating "full", "partially", and "no consideration", which could correspondingly lead to sufficient or insufficient TPACK evaluation consequences.

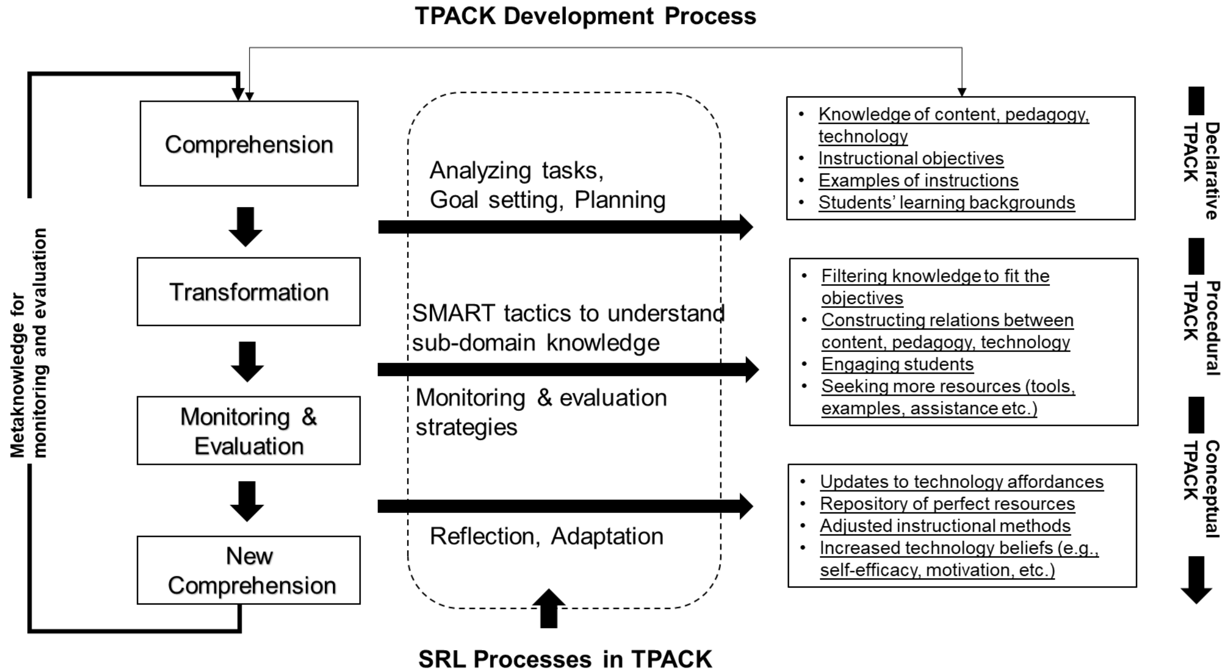
SRL in New Comprehension

At the final stage, teachers summarize what they have learned from the task and make adaptations to TPACK comprehension. Their SRL activities involve reflection and adaptation. Teachers can reflect on whether their technological practices satisfy the demands of TPACK framework. They can revisit strategies to see which are effective for learning about TPACK. Teachers also adjust self-beliefs and motivation in relation to technology. The consequences of their reflections can lead to changes that impact their long-term TPACK development.

The CoTMEC$^+$ model (Figure 4) presents a new perspective on TPACK development, which unveils the cognitive processes hidden in the previous TPACK theoretical framework. We consider it as a promising model expanding the current state of work developing TPACK as a theory. The CoTMEC$^+$ model is aligned with the reconceptualization of TPACK mentioned previously and can lead to methodological reconsiderations. We discuss these TPACK measurement considerations below.

Figure 4

The SRL Processes in the CoTMEC$^+$ Model



SRL and TPACK Measurement

Current Approaches to Measuring TPACK

The measurement of TPACK is a vital area of research in the TPACK literature. There are a number of different measuring approaches developed to assess teachers' TPACK. One type of research is characterized by a more static conceptualization of TPACK, with the emphasis on the use of self-reporting that relies on reporters' perceptions and beliefs. For instance, when a self-reported questionnaire is administrated, teachers are asked to provide their perceptions of knowing in light of various sub-domain knowledge outlined in the integrative TPACK framework. An interview and a semi-structured interview use open-ended questions to understand teachers' experiences of learning about TPACK. According to the recent review by Willermark (2018), who surveyed TPACK-related empirical publications from 2011 to 2016, around 70% of articles adopted self-reporting as the effective tool to investigate teachers' general TPACK knowledge (e.g., Schmidt et al., 2009), specific TPACK knowledge (e.g., Jen et al., 2016) or experienced TPACK knowledge (e.g., Koh & Divaharan, 2013). For example, Lee and Tsai (2010) used a 30-item TPACK-Web Survey to explore preservice teachers' TPACK in the context of web-based instruction. Regarding the interviews, participating teachers are asked to answer a series of pre-determined questions like "what are the advantages/disadvantages of calculator usage and the effects on the teaching and learning process and environment?" (Ozgun-Koca, 2009). Then researchers conduct text analysis to understand teachers' TPACK. The positive side of self-reporting methods is that they, particularly self-reported questionnaires, embrace economic aspects in terms of implementation, administration, and scoring (Scherer et al., 2017) whereas the biggest weakness is given to the issue of reliability and trustworthiness (Veenman, 2011). In addition, self-reporting measurement often provides self-assessment of confidence in TPACK rather than their TPACK in practice (Lawless & Pellegrino, 2007), and hence does not capture changes in TPACK comprehension that is induced by transformation (Voogt et al., 2013).

Alternatively, performance-assessment methods have risen to represent the transformative nature of TPACK and provide opportunities for teachers to demonstrate what they can actually do with technology in their practice (Angeli & Valanides, 2009; Voogt et al., 2013). Performance assessments draw on the participants' artifacts, usually lesson plans that are designed for an instruction task and examine TPACK with a sophisticated evaluation rubric. For instance, Koehler, Mishra, and Yahya (2007) used this method to estimate student teachers' TPACK while they were designing an online course. Additionally, performance is assessed on how TPACK is operationalized

(Kafyulilo et al., 2015; Stoilescu, 2015). In the study conducted by Graham, Borup, and Smith (2012), the technology integration reasoning that teacher candidates produced before and after the task was investigated. Participants' articulations were analyzed to determine which sub-categories of TPACK could help technology integration and what rationales student candidates possess for using technology as part of their instruction. Performance measurement is of prevalence as it focuses on TPACK occurring in teaching processes or activities. It captures TPACK as procedural knowledge in the context of reasoning about technology adoption. As stated, this method is context-specific and can precisely estimate the TPACK of the students (Akyuz, 2018; Schmidt et al., 2009). However, such a measurement is challenged by the issue of trustworthiness (Koehler et al., 2012). The available solution is to report reliability between different raters involved in evaluating TPACK performance.

Blending Measurement and Intervention

While these methods have been consolidated in understanding teachers' TPACK, they are limited by separating measurement and intervention. That is to say, research that uses the methods mentioned above first assess TPACK and then provides solutions for improving TPACK. The advantage is that the retrospective solutions might be decontextualized and general. However, we have discussed in previous sections the associations between TPACK and SRL. Succinctly, the degree of teachers' engagement in SRL could determine how successful they would be in TPACK learning. Thus, we propose a novel measuring method that can measure the transformative processes whilst promoting TPACK. An example of such type of assessment would be the use of technology-rich learning environments (TREs) to promote TPACK. A TRE is broadly referred to as a learning environment with instructional purposes that uses technology to assist learners in obtaining goals of teaching (Lajoie & Azevedo, 2006). TREs embrace an array of forms like intelligent tutoring systems, learning games, simulations, or artificial intelligence. TREs allow learners to practice skills deliberately, and in the meantime, they can accelerate the acquiring process by providing cognitive, metacognitive, and motivational scaffolds (Jang et al., 2017; Lajoie & Azevedo, 2006). The nature of scaffolding is to conduct dynamic and ongoing assessments (Lajoie, 2005). With advanced technology and techniques, TREs could diagnose the occurrence of a learning impasse and afford supports accordingly. For instance, TREs can recommend multiple sources of information when a student struggles with online information seeking. Also, TREs can prompt problem-solving strategies and metacognitive questions to have students become an independent learner. Therefore, TREs hold the potential to realize the measurement and intervention in a simultaneous venue.

In the context of TPACK development, TREs can assess and scaffold teachers' self-regulatory processes when they are performing tasks and therefore achieve the goals of TPACK. Three examples represent the lines of research that leverage TREs to support TPACK development. Kramarski and Michalski (2009, 2010) are pioneers in this area who adopted a web-based learning environment (WBLe) in TPACK development. WBLe contains various multimedia and hypertext tools and offers teachers the opportunities to learn how to teach about the subject matter by integrating technological tools. Teachers can present abstract contents into more concrete forms with images, animation, video clips, and audios. The hypertext environments of the

WBLs enable interactivity, and self-directed learning as teachers can build their learning paths by determining which links to follow. Furthermore, WBLs is a powerful metacognitive tool that promotes SRL abilities via metacognitive prompts (cf. Kramarski & Michalsky, 2009). Teachers ought to identify the most appropriate media representations and justify how to use these representations to maximize teaching and learning. In their findings, participants who worked in WBLs outperformed their counterparts with no WLBs in terms of TPACK comprehension and designing TPACK-based lessons (Kramarski, 2010).

Angeli and colleagues (2015a) developed e-TPACK, an adaptive e-learning technology for the interest of TPACK. As introduced, e-TPACK is “is a personalized e-learning system that is both adaptive and adaptable while the control of the adaptation process is shared between the users and the system” (Angeli et al., 2015b, p. 3060). Being adaptive, the system identifies users’ learning trajectories based on tracking user-system interactions that include teachers’ actions on the system and their self-rating of cognitive loads. With the prototypes, e-TPACK individually gives assistance. In their second version, the e-TPACK visualizes teachers’ learning process in the designed user interface and therefore triggers teachers to reflect on and regulate their progress. The subsequent empirical study showed that participants who learned with e-TPCK outperformed the those in the control group without e-TPACK in terms of TPCK competencies (Christodoulou, 2018).

Similar to the e-TPACK system, Poitras (Poitras et al., 2017; Poitras & Fazeli, 2016) designed an adaptive learning system called nBrowser for the interest of TPACK. The nBrowser is designed as a metacognitive learning tool to support preservice teachers in regulating their own learning while designing technology-integrated lesson plans. The nBrowser is characterized by its learner model that is continually updated by the system during the process of learning to capture students' learning trajectories. The system then delivers instructional content (e.g., hints, prompts, feedback, examples, etc.) in response to the analysis of the learner model and the detection of obstacles to achieve the desired outcomes. Meanwhile, the nBrowser collects information on how learners use the contents to figure out impasses. The system traces the learners' learning progress to provide appropriate feedback. With respect to the tracing mechanism, nBrowser takes advantage of computer logs to identify users' self-regulatory behaviors. Technologies embedded in TREs are capable of writing these behaviors to student log files (e.g., Azevedo et al., 2017; Nesbit et al., 2007; Taub & Azevedo, 2018). The underlying assumption is concerned with the new conceptualization of SRL as a sequence of events that can serve as observable indicators about cognition that students create as they engage with a task (Winne & Perry, 2000, p. 551). For example, taking notes is a log event that signals that a student comprehends information by recording, clarifying, organizing materials in a text (Bonner & Holliday, 2006). When a student highlights or italicizes a certain piece of information in the note, the event makes an inference that the student is more likely to control their comprehension. The method of using traces to measure SRL is usually implemented in TREs because the wide range of traces generated in TREs can capture SRL dynamics in real-time in a naturalistic setting (e.g., Bernacki, 2018; Biswas et al., 2014; Cerezo et al., 2019; Deekens et al., 2018; Lajoie et al., 2014; Siadaty et al., 2016).

As a training platform, the nBrowser facilitates TPACK acquisition through fostering teachers' SRL. The evidence from their empirical study shows a strong relationship between teachers' efforts to monitor and evaluate online information and their performance in designing technology-integrated lessons (Huang & Lajoie, 2021; Poitras et al., 2018; Poitras et al., 2018). In sum, these afore-mentioned projects particularly emphasize the effect of SRL on TPACK and combine intervention and measurement tools to obtain a deeper understanding of the participants' SRL actions in conjunction with the scaffolding aids to enhance TPACK acquisition and practice. Moreover, the success of these projects suggests the significance of the theoretical ground that conceptually models the associations between SRL and TPACK. As such, the proposed CoTMEC^{+} model can be expected to be an effective model that instructs future TPACK research.

Conclusion

Emerging technologies are playing an imperative role in modern education and reshaping the modes of teaching and learning. For teachers working in TREs, it is of paramount significance to construct a solid TPACK system, so they can utilize technologies to optimize their instructional capacities and support students attaining academic success. Current research in TPACK is limited in its abilities to clarify the construct and provide an effective method to assess and scaffold the cognitive processes underlying development (Krauskopf et al., 2015). To this end, this paper serves to initiate solutions. First, TPACK is reconceptualized as knowledge represented by declarative and procedural forms. The declarative form is equivalent to the integrative TPACK views (Mishra & Koehler, 2006), denoting what teachers endeavor to learn from education and training programs. The procedural form relates to the essence of the transformative perspectives (Angeli & Valanides, 2009) concerning TPACK teachers apply to accomplish an authentic technology-infused task. In addition, the novel concept assumes that developing TPACK is a four-stage cyclical process. In the different stages, teachers learn different forms of TPACK and produce distinguished outcomes. The purpose of modeling TPACK development stepwise is to outline the underlying cognitive processes through the lens of SRL theory. In brief, teachers retrieve prior knowledge, analyze conditions, and set specific goals in the comprehension stage. When transforming basic knowledge domains to more sophisticated ones, teaches adopt various strategies to maintain a higher level of performance. Next, teachers monitor and evaluate their performance in relation to the pre-defined goals and external criteria, i.e., students' satisfaction. Finally, teachers translate new comprehension of TPACK from the current task to future teaching practices. The reconceptualization also induces the changes in measuring TPACK, shifting measurements from aptitude-based (assessing what teachers know) to event-based (assessing what they do). Thanks to the affordances of SRL research, there are great opportunities to draw on TREs as a platform and advanced analytical techniques to track teachers' SRL behaviors and then make inferences to TPACK competencies.

In conclusion, this paper provides potential solutions to the existing criticism of TPACK research. We first respond to the debate regarding TPACK as integrative or transformative. We present the new concepts in favor of the argument that the TPACK framework explores how teachers transform the declarative form of knowledge to the procedural form to address practical teaching tasks. Second, the proposed CoTMEC$^+$

model holds the potential to clarify the boundaries of distinguished sub-domains. To figure out the issue, some studies focused more on determining whether the learning activities are domain-general or domain-specific (Cox & Graham, 2009). Some made explanations from models of conceptual changes (Krauskopf et al., 2015). We leverage the lens of SRL theory and assume that different level of TPACK relates to the degree of engagement in SRL activities. Hight SRL generates in-depth TPACK representations, including those confounding domains (e.g., TCK, TPK) and TPACK as meta-knowledge. Accordingly, this paper contributes to improving research into TPACK and formulating TPACK as a coherent theory (Graham, 2011). To support the assertions of the proposed model, we propose two areas that deserve future empirical investigation. First, more empirical evidence is needed to support our understanding of how teachers' SRL mediates learning TPACK. Secondly, it will be important to identify whether teachers show different SRL processes when they show different levels of TPACK competencies.

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Bridging Text

The aim of Chapter 2 was to articulate and justify the conceptual relations between TPACK and SRL. The proposed CoTMEC$^+$ model postulates that TPACK development is stepwise, consisting of four essential stages. Teachers construct the deep cognition about technology use through actively regulating the transformation of independent knowledge domains of content, pedagogy, and technology into a sophisticated mental model. In the process, teachers enact a wide array of self-regulatory activities such as analyzing tasks, goal setting, monitoring, evaluating, and reflecting to diagnose and resolve these obstacles to their learning about TPACK learning and technology adoption. Chapter 2 proposes measuring TPACK by means of assessing and scaffolding teachers' SRL with advanced technology. Based on the new conceptualizations, implications were raised to move the field forward by examining two questions: 1. Do teachers' SRL mediate their learning of TPACK?; 2. Are different SRL processes associated to different TPACK competencies?

In Chapter 3, I present an empirical study that answers the first question. The study explains how teachers' self-regulatory processes influence solving an instructional task that requires the integration of appropriate technologies. Mixed methods were used to examine the cognitive and metacognitive regulatory processes in designing a math lesson plan within the nBrowser. The paper was co-authored with my supervisor, Dr. Susanne Lajoie, and Dr. Eric Poitras, and Shan Li. The data used in this study is retrieved from the research Dr. Poitras conducted in 2015. As the primary author, I was responsible for the literature review, research questions and hypotheses, data analysis, and writing the original draft. Shan Li helped with the data analysis and revisions. Dr.

Lajoie and Dr. Poitras supervised the research and provided feedback to writing. The paper has been published in the *British Journal of Educational Technology*.

CHAPTER 3

Latent Profiles of Self-Regulated Learning and Their Impacts on Teachers' Technology Integration

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Abstract

Past research shows that both teachers' technological pedagogical content knowledge (TPACK) and their engagement in metacognitive activities are essential to technology integration in the classroom. However, the interplay between teachers' TPACK ability and their metacognitive skills is still underexplored, especially in the context of developing technology-infused lesson plans. This study examined how the interrelations among metacognitive activities and TPACK constructs affected preservice teachers' technology integration in instructional design. Sixty-four preservice teachers designed a lesson with nBrowser, a computer-based learning environment (CBLE[3]) that helps teachers incorporate technology into instruction by promoting self-regulated learning (SRL). Drawing on the lesson plans, we extracted six types of metacognitive processes preservice teachers exhibited while solving the task and generated two distinct SRL profiles according to the identified latent profile of metacognitive patterns. The competent self-regulated learners demonstrated more efforts in metacognitive monitoring activities than the less competent self-regulated learners in regulating their task solving processes. When comparing TPACK comprehension and design performance between the two profiles, the competent self-regulated learners outperformed the less competent self-regulated learners on comprehension and design outcomes. This study provides deep insights into teachers' self-regulation in CBLEs and emphasizes the pivotal role of metacognition and SRL in teachers' TPACK development.

[3] A CBLE is one type of TREs. I use the two terms interchangeably in the dissertation.

Keywords: metacognitive processes, self-regulation of learning, TPACK, technology integration

Latent Profiles of Self-Regulated Learning and Their Impacts on Teachers' Technology Integration

Advanced technologies in education are becoming more commonplace, and teachers are starting to leverage technologies to present abstract subject topics in a less complex manner and adapting instructional strategies to students' individualized learning needs (Lawless & Pellegrino, 2007). Teacher education and professional development programs provide training to promote teachers' technological skills in an integrative manner to ensure student success (Trust, 2018). Teachers' technology integration is related to their knowledge of content, pedagogy and technology (Harris, 2005; Koehler & Mishra, 2005; Mishra & Koehler, 2006; Pierson, 2001), described as technological pedagogical content knowledge (TPACK) that explains the complex interplay between these different factors in planning lessons. (Harris, 2005; Koehler & Mishra, 2005; Mishra & Koehler, 2006, 2008; Thompson & Mishra, 2007). Scholars theorize TPACK as a conceptual framework, concentrating on how teachers design ways of teaching concrete topics, how teachers implement technologies in pedagogical ways, and how teachers use technologies to present difficult content and help students develop new knowledge based on existing ones (Angeli & Valanides, 2009; Cox & Graham, 2009; Koehler & Mishra, 2009; Mishra & Koehler, 2006). It is imperative for teachers to develop TPACK as procedural knowledge to monitor and control their practices of using pervasive and emerging technologies. In doing so, teachers can conceptually understand TPACK and develop technology integration skills from a beginning novice to an expert level (Krauskopf et al, 2015).

Procedural knowledge refers to the application of knowledge for accomplishing a specific task (Winne, 2011). The application of procedural knowledge calls for metacognitive activities like monitoring, evaluating, reflecting and adjusting that mediate self-regulated learning (SRL). Research suggests that self-regulated learners are highly aware of performing these processes to regulate their learning and gain increased academic achievements (Azevedo & Cromley, 2004; Winne, 2001; Winne & Hadwin, 1998; Zimmerman, 2002). Empirical evidence demonstrates that preservice teachers who received metacognitive scaffolding had substantial TPACK gains and improved in their TPACK-related lesson design skills (Kramarski & Michalsky, 2009, 2010; Poitras et al., 2018). However, a systematic understanding of how SRL processes mediate preservice teachers' efforts to build TPACK is still lacking. We claim that this issue can be tackled through novel approaches to measurement, allowing researchers to model the deployment of SRL processes during learning and task performance to gain insights into mental model development.

This study aims to model the interrelations amongst SRL and TPACK constructs in the context of preservice teachers using nBrowser (Poitras et al., 2017), a computer-based learning environment (CBLE) designed to facilitate instructional planning and learning about the affordances of technology in the classroom. We use latent profile analysis to identify distinctive profiles regarding teachers' self-regulation and metacognition in the context of developing TPACK. This study could inform researchers about the specific characteristics of self-regulation and metacognition in teachers. This research also has implications for how metacognitive scaffolding can promote teachers' TPACK acquisition by modeling specific SRL abilities.

Conceptual Framework

Conceptualizing TPACK

In this study, we conceptualize TPACK as procedural knowledge critical for teachers' technology integration practices. The term "procedural" implies the idea of adapting the knowledge application to conditions, i.e., deciding when and how to use what has been learned and interpret why to do so. As Winne (2011) articulates, procedural knowledge in some ways models an "IF-THEN-ELSE" production system. "IF" produces a condition where a problem is identified. The mechanism of "THEN" creates solutions that might be able to solve the problem. "ELSE" concerns the monitoring of the solution and evaluate its effectiveness. In this way, we assume TPACK requires a deep level of procedural knowledge since we expect teachers to critically analyze the affordances and constraints of conditions (IF) where TPACK is applied and monitor and control TPACK solutions to different conditions (THEN-ELSE). This assumption is in line with technology mapping models (Angeli & Valanides, 2009), whereby TPACK development requires teachers' technological knowledge be applied to abstract topics that are difficult to present via traditional approaches and to materials whereby technology makes it easier for learners to learn.

Procedural knowledge subsumes what learners have acquired and stored in long-term memory thereby leading to a conceptual understanding of the complexity of a subject domain. There exist two perspectives of the TPACK framework in the literature. The integrative view (Mishra & Koehler, 2006) outlines TPACK as integration of sub-domain knowledge in content, pedagogy and technology. The transformative view (Angeli & Valanides, 2009) defines TPACK as a unique type of knowledge as a consequence of deliberate practices. In a sense, our reconceptualization balances the two perspectives and highlights a mental process underlying how TPACK is developed from a lower level (i.e., how teachers literally represent TPACK) towards the construction of conceptual knowledge of TPACK.

Krauskopf et al. (2015) emphasized TPACK as "a construct comprising teachers' meta-conceptual awareness of the demands of the teaching task at hand, the teachers' knowledge in the sub-domains, and the contextual constraints" (p. 56). Hence, defining TPACK as procedural knowledge allows researchers to specify the mental processes while teachers are developing TPACK. The procedure includes analyzing task conditions, identifying problems, planning goals and solutions, monitoring solutions and evaluating and revising solutions. TPACK can be developed only by the effective enactment of these processes. We elaborate on the role that self-regulated learning plays in fostering the development of TPACK procedures in the following section.

SRL Processes in Constructing TPACK

Information processing theories of SRL (IPT-SRL, Winne & Hadwin, 1998) conceptualize teacher learning as a process of mental model construction and adaptation mediated by metacognitive monitoring and control processes (Azevedo, 2009; Butler & Winne, 1995; Corno, 1986; Pintrich, 2000; Schunk, 2008; Winne, 2011). Such a model assumes that metacognitive monitoring is omnipresent throughout the entire regulatory process rather than only during and after learning phases (Azevedo et al., 2011; Meijer et al., 2006; Winne, 2011). In the preparatory phase, learners can metacognitively monitor and evaluate their understandings of the task requirements, the adequacy of relevant prior knowledge, and the development of concrete goals and sub-goals. Metacognitive processes also guide students, enabling them to think about the effectiveness of study tactics and strategies critically and adaptively modify study techniques for the sake of task goals (Winne & Hadwin, 1998). Therefore, SRL is not considered as strictly time-sequenced since metacognition can be visible wherever it is necessary and create updates as well as adjustments. Furthermore, research that examines SRL delineates a wide range of specific processes relating to metacognition. Zimmerman (1986, 2002) analyzed successful self-regulated learners' behaviors and identified several key metacognitive processes like planning, self-instructing, self-monitoring and self-evaluating. Similarly, Pintrich (2000) and Winne and Hadwin (1998) outlined metacognitive processes in accordance with different learning stages, such as goal setting in the preparatory stage, reflecting in the appraisal phase and so on.

We make several assumptions in regard to the relationships between SRL and TPACK constructs examined in this study. First, metacognitive processes foster successful technology integration in that these activities enable teachers to actively exert procedural TPACK as meta-knowledge in developing specific teaching objectives, integrating pedagogical and technological strategies into instructions, and self-assessing performance. According to the information-processing model of SRL (Winne & Hadwin, 1998), technology integration should be a goal-oriented process. Teachers develop goals and sub-goals that are complied with the TPACK framework. Furthermore, teachers need to use these goals as standards to monitor and evaluate the alignments between teaching objectives, pedagogical and technological strategies. After that, teachers could make modifications to satisfy the goals and TPACK requirements. In doing so, we are able to understand how teachers develop TPACK by examining how they engage in SRL. For instance, a teacher compares a virtual reality (VR) device against videos to determine which one is useful to create an immersive environment (goal setting). If they think VR is accessible and applicable, and students feel interested in it (monitoring), the teacher will decide to adopt VR (controlling). Otherwise, they might use regular videos (controlling). This example shows that the teacher is enacting SRL and building TPACK as the procedural format in the meantime, i.e., carrying out activities to accomplish the task. Furthermore, various cognitive tactics and strategies will lead to different products that refer to newly created information (Winne & Hadwin, 1998). For instance, the strategies of “monitoring” and “elaboration” enable teachers to justify how subject matter and technological knowledge could be linked and subsequently produce TPACK. Consequently, we hypothesize that teachers’ engagement in regulated metacognitive processes mediates their technology integration through developing TPACK towards the procedural form of knowledge. Failure in understanding procedural TPACK more likely undermines the effectiveness of technology use. Second, we assume that teachers’ metacognitive processes should be observed before, during and after their technology-based instructions since metacognitive processes are omnipresent. For example, teachers can monitor goal setting to assess if the goals are relevant to the tasks. They can also evaluate one specific technology solution to examine if using that given tool facilitates or impedes learning and teaching.

Research Background

In support of these claims, past studies have shown that interventions targeting teacher SRL processes do improve teacher’s ability to plan instructional activities where technology is used to enhance student learning. For example, Kramarski and Michalsky (2009, 2010) found improvements in preservice teachers' metacognitive processes in planning, action and performance, as well as evaluation phases. Their quasi-experimental studies illustrated that teachers improved their TPACK comprehension and design skills once their metacognitive strategies were enhanced. Furthermore, teachers from the experimental group, who received metacognitive prompts regarding reflection strategies, outperformed those from the control group on measures of TPACK development. Poitras et al. (2018) found similar findings where dynamic metacognitive scaffolds better-supported preservice teachers in assimilating TPACK related information into their lesson plans than teachers in a static scaffolding condition. A comprehensive model is needed that links the inherent constructs of SRL to teacher learning and instructional planning to enhance TPACK.

Contemporary research in SRL conceptualizes the relevant constructs as events that dynamically unfold throughout learning, where any given SRL processes comprise of a temporal beginning and end in particular contexts (Veenman, 2011; Winne, 2010; Winne & Perry, 2000). Online trace methodologies (e.g., thinking-aloud, log files) capture the deployment of observable indicators of these latent constructs, allowing for more precise and nuanced identification of metacognitive processes involved in learning (e.g., Biswas et al., 2014; Cho & Yoo, 2017; Greene & Azevedo, 2010; Poitras et al., 2017; Taub et al., 2019). This approach is advantageous in the context of computer-based learning environments where real-time data regarding students' actions before, during and after learning. This enables the systems to deliver scaffolds in an adaptive manner by tailoring their characteristics to the specific needs of different learners (Azevedo et al., 2012; Azevedo & Cromley, 2004; Azevedo et al., , 2007). One of the main limitations of this approach, however, is the validity of the inferences drawn from the log trace data. There is a need to corroborate claims drawn from the process data by aligning it with outcomes. This study builds on recent approaches to tackling this issue by applying student-profiling methods such as Latent Profile Analysis (Barnard-Brak et al., 2010; Jang et al., 2017; Lau et al., 2017) to model the relationships between SRL and TPACK outcomes.

Research Rationale

This study conducts a careful analysis of teachers' lesson plans to capture metacognitive processes at a micro-level. Lesson planning is an important element in developing teachers' professional expertise. Designing a technology-infused lesson requires teachers to provide clear teaching objectives (goal-setting), carefully designed technological strategies to represent contents and manage instruction and students (strategy planning), approaches to assessing students' understanding of the contents with technologies (strategy enactment), and summaries of teaching performance (reflection). These essential components map on SRL models, representing critical processes of goal setting, strategy planning, strategy enactment and monitoring, and reflection respectively. As such, analysis of lesson plans serves to identify teachers' instructional goals, planning and justifications of their reasoning of selecting and implementing technologies in teaching as well as their reflective remarks (Harris et al., 2010; Koehler & Mishra, 2009). Lesson design demonstrates teachers' higher order thinking skills (i.e., SRL) and helps them achieve in-depth TPACK comprehension.

Furthermore, an analysis of lesson planning is advantageous over other measurements of SRL or TPACK since it is unobtrusive and generates objective data.

Additionally, the microanalysis of SRL offers opportunities to gain insights into teachers' metacognitive processes. While the contemporary SRL models conceptually describe phases and the regulating process in general, the microanalysis outlines specific SRL processes that can be observed while students are enacting a specific task. Accordingly, this analytical method connects the actual observable SRL processes with conceptual models of areas of self-regulation (Greene et al., 2010). Azevedo and colleagues (Azevedo et al., 2007; Azevedo et al., 2004; Greene & Azevedo, 2009; Greene et al., 2010) created the microlevel SRL framework, identifying approximately 30 concrete regulatory processes that pertain to areas of cognition, motivation, behavior and context. For example, feeling of knowing and self-questioning are two instances of the monitoring process. These SRL-relevant processes are captured through coding artifacts (e.g., lesson plans in this study) and making an inference about SRL events. Micro-level SRL processing data provides a sense of what and how specific activities are performed during learning, and thus reveal what micro-level SRL processes make an impact on learning outcomes.

Moreover, we conducted latent profile analyses (LPA) to create the preservice teachers' metacognitive profiles, which illustrates the heterogeneity of teachers' self-regulatory processes. Our assumption is that SRL is domain-specific (Poitras & Lajoie, 2013) and that SRL is influenced by factors like prior personal knowledge, and self-efficacy. For example, students with higher self-efficacy might aim to accomplish several goals, whereas those who are low on self-efficacy may limit their goals. LPA provides benefits in developing a conceptual understanding of the individual variations in teachers' self-regulation and their impact on TPACK achievements (Barnard-Brak et al., 2010; Jang et al., 2017; Lau et al., 2017). Consequently, to obtain a greater picture of preservice teachers' metacognitive processes in technology integration practices, this study aims to answer the following questions.

1. What profile of metacognitive processes can be identified while preservice teachers were doing a technology integration task?
2. Is there a difference in TPACK comprehension between preservice teachers with distinctive metacognitive profiles?
3. Is there a difference in technology-integrated skills between preservice teachers with distinctive metacognitive profiles?

Previous empirical studies by Kramarski and Michalsky (2009, 2010) indicated preservice teachers with metacognitive scaffolds had better TPACK comprehension and design skills in technology integrating tasks. Based on their findings, we hypothesized that preservice teachers who actively enact metacognitive processes would have more gains in TPACK comprehension and higher TPACK-based design performance, compared to their counterparts with less active metacognitive processes.

Methods

Participants

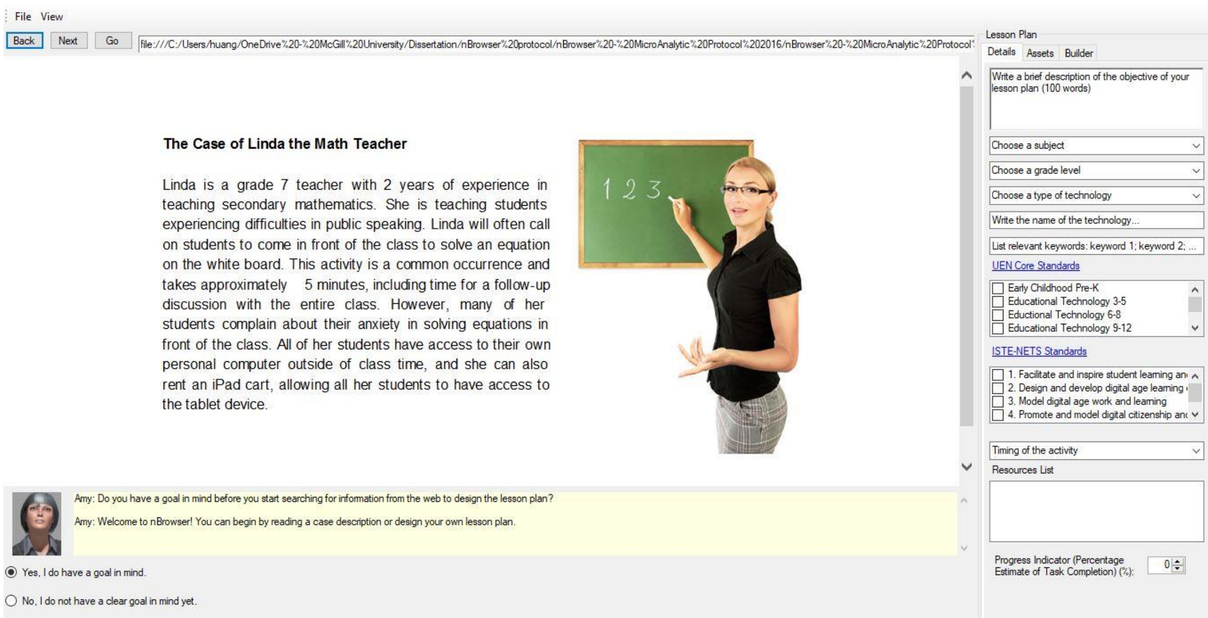
The sample in this study includes 68 student teachers (Female = 53) with the mean age of 23 years old (*SD* = 4.7). The participants were enrolled in the College of Education at a public university in the western region of the United States, including 51 bachelor students and eight students in the master program. The sample has an average GPA of 3.5 (*SD* = 0.4). Approximately half (46%) of them reported that they have enrolled or completed a practicum experience in PreK-12 classrooms. Of the participants, 28 (41%) had reported having opportunities to effectively demonstrate or model combining content, technologies and teaching approaches in a classroom lesson. Ethics approval was obtained from the institution where participants were recruited. All students were compensated for partial course credit for their participation. We excluded the data from four individuals due to technical issues with the recording equipment. Thus, data from 64 participants were analyzed.

Computer-Based Learning Environment

Participants were required to design a technology-infused lesson using an intelligent web browser called nBrowser (Poitras et al., 2017). The nBrowser was designed to help preservice teachers incorporate technology into instruction with the consideration of subject matter, pedagogical approaches, and students' demands. The nBrowser provides participants with different interfaces, allowing participants to shift between interfaces whenever it is necessary (Figure 5). The Details panel presents the participants with the learning tasks (e.g., Linda's case in this study) and supports them to describe the objectives and the characteristics of their lessons. In the Assets panel, participants can seek the sources of information online and evaluate to what extent the information is useful for their plans. The Builder panel enables participants to write down their lesson designs. Participants can also request help for the lesson structure and sample design in this panel.

Figure 5

The nBrowser User Interface and Linda' Case



Design and Procedure

Participants were first instructed to read and sign the consent form indicating their agreement to participate in the study. Then the participants complete the demographic questionnaire and the pre-knowledge test concerning their TPACK comprehension. Next, participants received video introductions about the functions of nBrowser. Once they clearly understood how to use the system, the learning session began. The entire learning session lasted approximately 60 minutes, within which participants needed to design a lesson plan to resolve an issue illustrated in a case study by leveraging the affordances of technology. During the process, the researcher would not communicate with the participants unless there were technical issues. The participants informed the researcher when they completed and submitted their designs. Subsequently, the participants were administered the post-test, which was identical to the knowledge pretest, which took 10 minutes.

Measuring Learning Outcomes

Learning outcomes of TPACK comprehension and design performance were obtained utilizing participants' pre- and post-TPACK questionnaires and lesson plans respectively. TPACK was measured by the Survey of Preservice Teachers' Knowledge of Teaching and Technology (Schmidt et al., 2009, the full questionnaire is presented in Appendix A). The survey consists of 47 items and investigates student teachers' TPACK from the following seven dimensions, i.e., (1) technology knowledge (*n* = 7; e.g., I keep up with important new technologies), (2) content knowledge (*n* = 12; e.g., I have various ways and strategies of developing my understanding of literacy), (3) pedagogical knowledge (*n* = 7; e.g., I can adapt my teaching style to different learners), (4) pedagogical content knowledge (*n* = 4; e.g., I am familiar with common students' understandings and misconceptions), (5) technological content knowledge (*n* = 4; e.g.,, I know about technologies that I can use for understanding and doing literacy), (6) technological pedagogical knowledge (*n* = 5; e.g., I am thinking critically about how to use technology in my classroom), and (7) technological pedagogical content knowledge (*n* = 8; e.g., I can teach lessons that appropriately combine literacy, technologies and teaching approaches). The survey adopts a 5-point Likert scale with the value "1" indicating "strongly disagree," while the value "5" indicating "strongly agree." The survey has an internal consistency of 0.75 to 0.92, across the seven dimensions, which is a high level (Schmidt et al., 2009). Participants' pre- and post-measurement scores were calculated according to the percentage score obtained on each scale.

Preservice teachers' integration design performance was measured by evaluating their lesson plans based on the Technology Integration Assessment Rubric (TIAR, Harris et al., 2010, Appendix B). TIAR includes four criteria, (1) curriculum goals and technologies that indicate using technology based on curriculum, (2) instructional strategies and technologies that indicate using technologies based on pedagogical strategies, (3) technologies selection(s) that indicates selecting technologies with consideration of curriculum goals and instructional strategies, (4) “Fit” that indicates aligning curriculum goals, instructional strategies and technology use. Each criterion is assessed using a 4-point scale, with “1” meaning a minimum performance and “4” meaning an excellent performance. The instrument is reported to obtain a high internal consistency using Cronbach’s Alpha (.911) and robust construct and face validities.

Data Analysis

Coding and Scoring Lesson Plans

To understand preservice teachers’ metacognitive processes, we segmented participants’ lesson plans into meaningful idea units (Chi, 1997), and coded the units with a specially developed coding scheme based on the microanalysis model of SRL (Azevedo & Cromley, 2004). We limited the scope of our analysis to six categories of metacognitive processes presented in Table 1. Initially, the first and second authors coded one lesson plan together to establish an understanding of each code. Then, two raters coded another 20 lesson plans independently to examine the interrater reliability. The result showed that our interrater reliability reached a high level of Cohen’ Kappa (.775, $p < .001$). After that, the researchers compared their codes, addressed the differences and completed the rest of the lesson plans. Similarly, four researchers evaluated participants’ lesson plans based on the scales indicated in TIAR, yielding a 90% inter-rater agreement.

Table 1

Coding Scheme for Metacognitive Activities

Codes	Description	Example
Expectation of adequacy	Expect that a certain type of instruction/tools will prove either adequate or inadequate given the current goal	"*By watching videos on the material at home from a specific website they will be able to have a feel for the classroom and the problem they need to solve*."
Self-explanation	Justify the selection of instructional strategies/tools	"*As such Khan Academy is a source that will be appropriate for building confidence when it comes to math it meets the following requirements:(1) the website gives you resources in order for you to type or select a specific math problem you need to solve*."
Progress Monitoring	Attend to steps or issues that facilitate or hinder students' learning processes	*"Students could check with a partner to see if they are doing it right, have a partner correct their work."*
Self-reflection	Reflect the lesson design and identify underlying or further issues or concerns to realize the designed plan	*"However, no matter what technology Linda uses, she needs to ensure that her class has a strong base knowledge of how to do math, so this would require her teaching them math in the class, and then letting them create the videos outside of class."*
Evaluation	Evaluate effectiveness of the selected instruction / tools	*"The students stand to benefit both from using the technology and practicing their public speaking skills/ math skills in a less anxious setting."*
Adaption	Indicate additional solutions to goals	*"After the lesson students will be given the assignment of visiting some of the recommended mathematics websites to work on other problems or play mathematical games"*

Latent Profiles of Metacognitive Strategies Use

Latent profile analysis (LPA) is a statistical modeling technique that identifies taxonomies or classes of individuals based on their common characteristics among participants with continuous predictors (Bartholomew, 1987). One major advantage of this approach is that LPA depends on less arbitrary criteria to select classes and provides formal statistical parameters to determine the appropriate number of classes (Vermunt & Magidson, 2003). There are relatively few assumptions in this approach, meaning there is no need for normal distributions. We performed LPA in Mplus 7.4 (Muthén & Muthén, 2004) to generate optimal profiles by referencing to the Akaike's information criteria (AIC), Bayesian information criteria (BIC), sample size-adjusted Bayesian information criteria (Adjusted BIC), entropy, the Bootstrapped Likelihood Ratio Test (BLR) and the Lo-Mendell- Rubin Adjusted Likelihood Ratio Test (LMR). The best-fitting model follows the fit statistics (1) AIC, BIC, Adjusted BIC should be smaller compared to other models specifying less or more classes; (2) entropy should be greater; and (3) BLR and LMR should be significant, i.e., the *p*-value is smaller than 0.05. We also consider that the clusters consisting of 5% or less of the sample are expected.

Results

Metacognitive Processes Identified from Technology Integration Tasks

Table 2 showed the descriptive results generated from the coding of metacognitive strategy categories, including the absolute, relative frequency, means and standard deviations. There were 885 codes in total, of which 405 (45.8%) codes were relevant to our metacognitive categories, in contrast to 480 (54.2%) irrelevant codes. The means of metacognitive codes (M = 6.3, SD = 3.4) revealed that each participant performed six metacognitive processes on average when designing a TPACK-based lesson. In terms of specific processes, self-explaining was the most used by participants, with the highest frequencies (107, 12.1%) and mean score (M = 1.7, SD

= 1.33). Adapting was the least frequent metacognitive activity (30, 3.4%) and means (M = 0.5, SD = 0.73). Other processes such as evaluating (n = 76, 8.6%), self-reflecting (n =67, 7.6%), progress monitoring (n = 67, 7.6%) and expectation of adequacy (n = 58, 6.6%) were moderately executed by participants, averagely 1-2 times in their design processes according to the respective statistical results.

Table 2

Descriptive Statistics of All Codes Regarding Metacognitive Activities

Metacognitive strategies	Absolute Frequency	Relative Frequency (%)	Mean	Stand Deviation
EOA	58	6.6	.9	.89
SE	107	12.1	1.7	1.33
ADP	30	3.4	.5	0.73
SR	67	7.6	1.0	1.24
PM	67	7.6	1.0	1.24
EVA	76	8.6	1.2	1.10
Relevant	405	45.8	6.3	3.4
Irrelevant	481	54.2	7.5	4.0
Total	885	/	13.8	6.11

Note. EOA = Expectation of adequacy; SE = Self-explaining; ADP = Adapting; SR = Self-reflecting; PM = Progress monitoring; EVA = Evaluating

SRL Profiles

To find the optimal LPA model, we generated solutions with 2, 3, and 4 classes and compared them against the fit indices. Moreover, we inspected the mean scores of each predictor variable between different profiles to assess the distinctiveness of the classes. Table 3 showed no substantial differences between different cluster models concerning the indices of AIC, BIC and adjusted BIC in general. However, both the BLR value and the LMR value were significant for a 2-cluster solution ($p < .001$, $p = .001$ respectively), indicating that the 2-class model was superior to a 1-cluster model. A 3-class solution did not significantly better than a 2-class solution, considering that the BLR value ($p = 1.00$) and the LMR value ($p = .279$) were not significant. The BLR and the LMR values of the 4-class solution indicated that it did not fit better than a 3-class solution. Furthermore, the entropy value of the 2-class solution was .894, indicating that 89.4% of subjects were correctly classified, which was considered high. Therefore, we deemed that the 2-class solution was optimal.

Table 3

Fit Indices for Different Models with the Number of Clusters Ranging from 2 to 4.

Model	AIC	BIC	Adjusted BIC	No. of free parameters	*p* BLR	*p* LMR	Entropy	Smallest cluster freq.
2 classes	684.2	705.8	674.3	10	.000	.001	.894	16(.250)
3 classes	683.9	714.1	670.1	14	1.00	.279	.833	12(.188)
4 classes	684.5	723.4	666.7	18	1.00	.423	.861	6(.093)

Note: *p*BLR = *p* values for the Bootstrapped Likelihood Ratio test, *p*LMR = *p* values for the Lo-Mendell-Rubin adjusted likelihood ratio test.

The final 2-class solution is presented in Table 4. The Class 1 comprised of 48 participants, accounting for 75% of the total participants. Class 2 was composed of 16 participants (25%). Regarding the frequencies of metacognitive categories, participants in both Class 1 and Class 2 made more efforts in Self-explaining (12.3% & 11.6%) and least efforts in Adapting (2.3% & 5.3%). Class 2 was also endorsed in Progress monitoring (12.6%). Therefore, participants in both classes were self-regulatory. Class 2 exhibited higher competence in metacognitive monitoring processes, which we labeled as *competent self-regulated learners*. In comparison, Class 1 fairly but minimally engaged in metacognitive processes, so it was labeled as *less competent self-regulated learners*.

Table 4

Descriptive Statistics of All Codes Regarding Metacognitive Activities in Two Groups

	The Competent self-regulated Learners (n =16)		The less competent self-regulated learners (n =48)	
Metacognitive strategies	Absolute Frequency	Relative Frequency (%)	Absolute Frequency	Relative Frequency
EOA	15	4.7	43	7.6
SE	37	11.6	70	12.3
ADP	17	5.3	13	2.3
SR	23	7.2	44	7.8
PM	39	12.6	28	4.9
EVA	23	7.2	53	9.3
Relevant	154	48.4	251	44.3
Irrelevant	164	51.6	316	55.7
Total	318		567	

Note. EOA = Expectation of adequacy; SE = Self-explaining; ADP = Adapting; SR = Self-reflecting; PM = Progress monitoring; EVA = Evaluating

Differences in TPACK Comprehension and Design Performance

Three independent t-tests were performed with SRL groups as the independent variable and pretest, post-test and learning gains as the three dependent variables to address the third research questions. We first checked the normality of the three dependent variables, and the Shapiro-Wilk test shows that the mean scores of the pretest, post-test and learning gains on two groups are normally distributed (all *p*s > .05). The *t*-test results in Table 5 illustrate that the mean score of pre-TPACK test for competent self-regulated learners (*M* = .77, *SD* = .06) was significantly higher than that for less competent self-regulated learners (*M* = .72, *SD* = .06), t (62) = 2.28, $p < .05$. A similar pattern was found in terms of the post-TPACK test; competent self-regulated learners had higher mean scores than their counterparts, t (62) = 2.86, $p < .05$. However, the means of learning gains of the competent self-regulated learners (*M* = .03, *SD* = .04) was higher than those of the less competent self-regulated learners (*M* = .01, *SD* = .05), but the difference was not statistically significant (t (62) = 1.35, $p = .182$).

Anther independent *t*-test was performed on the TIAR as the dependent variable to examine the difference of design performance. Shapiro-Wilk test indicates a normal distribution of the dependent variable, evidence by observed p-value greater than 0.05. The results indicated that there was a statistically significant difference between two groups in terms of the lesson plan evaluation with TIAR, t (62) = 2.271, $p < .05$, which suggests that the competent self-regulated learners outperformed the less competent self-regulated learners regarding the technology-enriched lesson designing performance.

Table 5

Independent T-Test Results of Pre-, Post-Test, Knowledge and TIAR between Two Groups

	More competent self-regulated learners (n =16)		Less competent self-regulated learners (n =48)		*t*	sig.
	M	SD	M	SD		
Pre-Test	.77	.06	.72	.06	2.28	< .05
Post-Test	.80	.06	.74	.07	2.86	<.05
KG	.03	.04	.01	.05	1.35	.182
TIAR	.67	.19	.56	.16	2.27	<.05

Note: KG = Knowledge gain; TIAR = Technology integration Assessment Rubric

Discussion

The purpose of the study is to understand how teachers' SRL facilitates their TPACK development. To this end, we asked participants to design a lesson plan with technology to solve the problem indicated in the case of Linda, the math teacher who complained about students' shyness and anxiety when solving math equations in front of the class. This is a complicated, ill-structured issue in classroom learning. In order to solve the problem with technologies, teachers are supposed to engage in regulatory activities like condition analysis (understand why students feel shy or anxious), setting goals (solve students' emotional issues), strategy enactment (select and implement technological solutions), monitoring (align technologies with subject matter and pedagogy) and control (determine the most appropriate technologies). Hence, using such a case offers us the opportunity to observe how teachers' self-regulation is performed.

This study has highlighted the importance of metacognition and SRL when teachers learn about TPACK and the affordances of technology while planning a lesson. In this study, TPACK is conceptualized as procedural knowledge, and we draw on SRL to probe into teachers' learning activities and phases in the course of the TPACK development. The underlying assumption is that there exists a common mental mechanism in SRL patterns and the concept of procedural knowledge. Moreover, we claimed that SRL is critical to learning and performance, but that their measurement in CBLEs during learning episodes should leverage different channels of data to corroborate claims. One such approach is to rely on latent profile analysis, a person-oriented approach to model metacognitive processes identified through microanalysis of task outcomes. It is noteworthy that the microanalysis of preservice teachers' lesson plans provided an overview of their metacognitive processes in the process of designing a technology-enriched lesson within a CBLE. The profiling results highlight the significant central role of metacognitive monitoring in planning technology-infused lessons, enabling comparisons across less and more competent groups of teachers.

On the one hand, the profile consisting of competent self-regulated learners could represent those who are more oriented towards monitoring and using self-explaining and self-reflecting strategies to evaluate their problem-solving progress. This type of SRL pattern is endorsed by SRL research since the high exposure to metacognitive monitoring processes leads to better performance and achievements (Azevedo & Cromley, 2004; Bannert et al., , 2015; Taub & Azevedo, 2018). For the interest of successful technology use, such an SRL pattern accounts for preservice teachers' understanding of the rationale and effectiveness of technologies, which accordingly makes conceptual and practical senses for developing technology integration towards an expert level.

On the other hand, the less competent self-regulated learner profile represents learners who are able to regulate learning but with minimum efforts. We do not consider the participants in the second profile as successful self-regulated learners due to the limited frequency of observed SRL behavior. This finding could indicate that teachers with less competent SRL profiles might only enact the metacognitive skills they already mastered while ignoring those skills (e.g., self-evaluating) that presented them with challenges. SRL is a skill that requires effort and practice to make it perfect. Less or minimum regulation efforts will not guarantee the active use of skills whenever they are needed. Ideal self-regulated students are able to proactively utilize key SRL and metacognitive processes (Zimmerman, 2002). However, most students have difficulty in deploying these processes. Consequently, researchers emphasize that SRL training or external supports could enhance students' regulating skills, and thus lead to learning gains (Azevedo et al., 2005; Azevedo & Cromley, 2004; Bannert et al., 2015; Kramarski & Michalsky, 2010; Krishna et al., 2019; Poitras, et al., 2018; Siadaty et al., 2016).

Overall, this study found that self-explaining activities, defined as justifying the selection of instructional strategies and technologies, was the most engaged process. Frequent exposure to self-explaining reveals that preservice teachers relied on their prior knowledge to assess their decisions concerning pedagogical and technological strategies. In doing so, we suggest that preservice teachers could have a conceptual understanding of TPACK, which in turn leads to high technology integration performance. A relatively high frequency in such metacognitive processes as expectation of adequacy, progress monitoring, self-reflecting and evaluating demonstrates that student teachers knew what technologies they were about to implement, critically thought of the affordances and constraints of tools, and self-evaluated the effectiveness of such tools. It might also suggest that preservice teachers' technology integration practice is oriented and monitored by clearly defined goals. Teachers engaged in relatively less adapting according to the descriptive statistics. Adapting in the study is defined as using additional technological solutions to achieve instructional goals for each student. It is possible that preservice teachers who are less experienced might be less aware of how to adapt to students' characteristics and learning contexts in technology-integrated lesson designs.

Regarding the differences of TPACK comprehension and design performance between the two identified profiles, our findings are in line with previous empirical studies, which suggest that preservice teachers with the competent SRL profile had a better conceptual understanding of TPACK than those in the less competent SRL profile. There is no significant difference in knowledge gains, which is not beyond our expectations. One reason could be that a one-time practice could not induce changes in knowledge acquisition since the improvement requires extensive effort, sufficient study hours and deliberate practice. Another reason lies in the measurement method. Specifically, participants might over- or under-report their TPACK comprehension, which influences the test results. Nevertheless, student teachers who demonstrated high competence in self-regulation had better design performance, in contrast to teachers with less competence. The significant difference in design performance also demonstrates the impact of metacognition and self-regulation on technology integration.

Conclusion

Limitations

We acknowledge some specific limitations of this study. There is a relatively small number of participants for the research. Meanwhile, participants in the study are limited to one university in the United States. They are not representative of the large population of preservice teachers. Overcoming these issues with larger samples and representation will lead to more generalizable findings and perhaps influence the number and type of SRL profiles identified. Thus, future research should include larger and diverse representative participants, and more theoretical considerations are necessary to guide the selection and identification of the latent profile classifications. In addition, we also raise a concern that the nBrowser scaffolds might influence of teachers' decisions of SRL enactment. The nBrowser is designed as a metacognitive tool supporting teachers' SRL, which includes goal setting menu, online search engine, a sample lesson and TPACK standards. Although these scaffolds are embedded in the interface design and non-obtrusive, we admit that they might exert subtle influence in teachers' self-regulation. For instance, a teacher might not review their lesson plans and compare it against the TPACK framework if there is no relevant information provided by the nBrowser. Such influence might change teachers' SRL behaviors and affect SRL profiles indirectly. As a consequence, further research should measure teachers' metacognitive profiles prior to and after using the system or adopt an experimental design with a control group to minimize the influences of the system.

Implications

Despite limitations, the study has scientific and practical implications. In terms of the scientific implications, examinations of teachers' metacognitive processes in this study enhance our understanding of teachers' self-regulation in the context of TPACK development. Extensive empirical research has revealed the different regulatory processes in response to the different contents and strategies involved in a task (Poitras & Lajoie, 2013). Domain-specificity of SRL has been reported in other domains, i.e., historical reasoning (e.g., Greene et al., 2010) and clinical reasoning (e.g., Poitras et al., 2018). The current research provided evidence that SRL is also domain-specific with respect to the development of TPACK. Hence, the important findings obtained from the present study not only inform researchers about what SRL processes they enact but also offer deeper insights into how teachers apply different self-regulatory processes in addressing authentic instructional tasks. Second, this study adopted the text analysis and person-oriented profiling method to identify metacognitive and SRL patterns, which enriches current research methods with respect to SRL in TPACK. Different from using self-reports (Kramarski & Michalsky, 2009, 2010) and trace methods (Poitras et al., 2018), we captured SRL processes from the written artifacts, i.e., lesson plans that reflect teachers' complex mental processes of retrieving knowledge about the topic, and how they address the diverse needs of students, learning unfamiliar technologies, monitoring and evaluating the implementation of technologies (Moos & Pitton, 2014). By analyzing the dynamic nature of lesson planning lent itself to better assessments of the temporal nature of SRL processes and the relationship between such processes and achievements pertaining to better lesson designs. Therefore, it is of great importance for scholars to employ different approaches to improve the accuracy of estimations of teachers' regulatory processes because teachers may go through the calibration process as a function of metacognitive activities during learning or task solving (Winne, 2010).

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Appendix A

Survey of Preservice Teachers' Knowledge of Teaching and Technology

Demographic Information

1. Your first name_____________, last name_______________
2. You Gender A. Female B. Male
3. Age: ____________________
4. School Year (e.g., Bachelor): ____________________
5. Program Major: _______________
6. Enrolled-Completed-Practicum-Experience-PK-12-Classroom A. Yes B. No
7. Describe a specific episode where you effectively demonstrated or modeled combining content, technologies, and teaching approaches in a classroom lesson. Please include in your description what content you taught, what technology you used, and what teaching approach(es) you implemented. If you have not had the opportunity to teach a lesson, please indicate that you have not.
   ____
8. Yeas in Program: ______________________
9. GPA: _______________________
10. Your email address: __________________________

Technology is a broad concept that can mean a lot of different things. For the purpose of this questionnaire, technology is referring to digital technology/technologies— that is, the digital tools we use such as computers, laptops, iPods, handhelds, interactive whiteboards, software programs, etc. Please answer all of the questions, and if you are uncertain of or neutral about your response, you may always select "Neither agree nor disagree."

Strongly Disagree = SD, Disagree = D,, Neither Agree/Disagree = N, Agree = A, Strongly Agree = SA

1. I know how to solve my own technical problems.	SD	D	N	A	SA
2. I can learn technology easily.	SD	D	N	A	SA
3. I keep up with important new technologies.	SD	D	N	A	SA
4. I frequently play around with the technology.	SD	D	N	A	SA
5. I know about a lot of different technologies.	SD	D	N	A	SA
6. I have the technical skills I need to use technology.	SD	D	N	A	SA
7. I have had sufficient opportunities to work with different technologies.	SD	D	N	A	SA
8. I have sufficient knowledge about mathematics.	SD	D	N	A	SA
9. I can use a mathematical way of thinking.	SD	D	N	A	SA
10. I have various ways and strategies of developing my understanding of mathematics.	SD	D	N	A	SA
11. I have sufficient knowledge about social studies.	SD	D	N	A	SA
12. I can use a historical way of thinking.	SD	D	N	A	SA

13. I have various ways and strategies of developing my understanding of social studies.	SD	D	N	A	SA
14. I have sufficient knowledge about science.	SD	D	N	A	SA
15. I can use a scientific way of thinking.	SD	D	N	A	SA
16. I have various ways and strategies of developing my understanding of science.	SD	D	N	A	SA
17. I have sufficient knowledge about literacy.	SD	D	N	A	SA
18. I can use a literary way of thinking.	SD	D	N	A	SA
19. I have various ways and strategies of developing my understanding of literacy	SD	D	N	A	SA
20. I know how to assess student performance in a classroom.	SD	D	N	A	SA
21. I can adapt my teaching based upon what students currently understand or do not understand.	SD	D	N	A	SA
22. I can adapt my teaching style to different learners.	SD	D	N	A	SA
23. I can assess student learning in multiple ways.	SD	D	N	A	SA
24. I can use a wide range of teaching approaches in a classroom setting.	SD	D	N	A	SA
25. I am familiar with common student understandings and misconceptions.	SD	D	N	A	SA
26. I know how to organize and maintain classroom Management.	SD	D	N	A	SA
27. I can select effective teaching approaches to guide student thinking and learning in mathematics.	SD	D	N	A	SA
28. I can select effective teaching approaches to guide student thinking and learning in literacy.	SD	D	N	A	SA
29. I can select effective teaching approaches to guide student thinking and learning in science.	SD	D	N	A	SA
30. I can select effective teaching approaches to guide student thinking and learning in social studies.	SD	D	N	A	SA
31. I know about technologies that I can use for understanding and doing mathematics.	SD	D	N	A	SA
32. I know about technologies that I can use for understanding and doing literacy.	SD	D	N	A	SA
33. I know about technologies that I can use for understanding and doing science.	SD	D	N	A	SA
34. I know about technologies that I can use for understanding and doing social studies.	SD	D	N	A	SA
35. I can choose technologies that enhance the teaching approaches for a lesson.	SD	D	N	A	SA
36. I can choose technologies that enhance students' learning for a lesson.	SD	D	N	A	SA
37. My teacher education program has caused me to think more deeply about how technology could influence the teaching approaches I use in my classroom.	SD	D	N	A	SA
38. I am thinking critically about how to use technology in my classroom.	SD	D	N	A	SA

39. I can adapt the use of the technologies that I am learning about to different teaching activities.	SD	D	N	A	SA
40. I can teach lessons that appropriately combine mathematics, technologies, and teaching approaches.	SD	D	N	A	SA
41. I can teach lessons that appropriately combine literacy, technologies, and teaching approaches.	SD	D	N	A	SA
42. I can teach lessons that appropriately combine science, technologies, and teaching approaches.	SD	D	N	A	SA
43. I can teach lessons that appropriately combine social studies, technologies, and teaching approaches.	SD	D	N	A	SA
44. I can select technologies to use in my classroom that enhance what I teach, how I teach, and what students learn.	SD	D	N	A	SA
45. I can use strategies that combine content, technologies, and teaching approaches that I learned about in my coursework in my classroom.	SD	D	N	A	SA
46. I can provide leadership in helping others to coordinate the use of content, technologies, and teaching approaches at my school and/or district.	SD	D	N	A	SA
47. I can choose technologies that enhance the content for a lesson.	SD	D	N	A	SA

Appendix B

Technology Integration Assessment Rubric

Criteria	4	3	2	1
Curriculum Goals & Technologies (Curriculum-based technology use)	Technologies selected for use in the instructional plan are strongly aligned with one or more curriculum goals.	Technologies selected for use in the instructional plan are aligned with one or more curriculum goals.	Technologies selected for use in the instructional plan are partially aligned with one or more curriculum goals.	Technologies selected for use in the instructional plan are not aligned with any curriculum goals.
Instructional Strategies & Technologies (Using technology in teaching/ learning)	Technology use optimally supports instructional strategies.	Technology use supports instructional strategies.	Technology use minimally supports instructional strategies.	Technology use does not support instructional strategies.
Technology Selection(s) (Compatibility with curriculum goals & instructional strategies)	Technology selection(s) are exemplary, given curriculum goal(s) and instructional strategies.	Technology selection(s) are appropriate, but not exemplary, given curriculum goal(s) and instructional strategies.	Technology selection(s) are marginally appropriate, given curriculum goal(s) and instructional strategies.	Technology selection(s) are inappropriate, given curriculum goal(s) and instructional strategies.
"Fit" (Content, pedagogy and technology together)	Content, instructional strategies and technology fit together strongly within the instructional plan.	Content, instructional strategies and technology fit together within the instructional plan.	Content, instructional strategies and technology fit together somewhat within the instructional plan.	Content, instructional strategies and technology do not fit together within the instructional plan.

Bridging Text

The aim of Chapter 3 was to explore the influence of teachers' SRL abilities in their TPACK achievements. The use of the nBrowser allowed participants to seek and transfer their knowledge through available online sources of information into the lesson design practice. It also facilitated participants to engage in the SRL process while performing the task. The qualitative analysis of teachers' lesson plans afforded opportunities to identify teachers' specific cognitive and metacognitive regulatory processes in the TPACK development. Findings obtained from latent profile analysis and independent t-tests demonstrated that teachers' TPACK development differed significantly across distinctive SRL profiles. The findings are in line with previous empirical studies and add strong support to the hypothesis that teachers' SRL abilities have a mediating and predictable effect on learning about TPACK.

In Chapter 4, I present an empirical study that investigated the nuanced differences of SRL processes in the TPACK context. This research examines teachers' SRL processes to determine: (1) whether teachers' SRL were iterative? (2) whether or not teachers' SRL processes were goal-oriented? (3) how teachers' SRL processes were monitored. The paper was co-authored with my supervisor, Dr. Susanne Lajoie. As the primary author, I was responsible for the literature review, research questions and hypotheses, data collection, analysis, and writing the original draft. Dr. Lajoie supervised the research and provided feedback to writing. The paper was published in Computers and Education.

CHAPTER 4

Process Analysis of Teachers' Self-Regulated Learning Patterns in Technological Pedagogical Content Knowledge Development

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Abstract

Self-regulated learning (SRL) has a predictable and instrumental effect on learning complicated knowledge. This study investigates the role of SRL in acquiring technological pedagogical content knowledge (TPACK), an important aspect of teachers' effective technology use. The present study identified several regulatory procedural patterns used by teachers in the context of their TPACK achievements. A computer-based context, nBrowser, was used to facilitate teachers lesson planning around technology usage. Teachers log file data were analyzed using process mining approaches. Findings indicate that high TPACK performers are more likely to perform self-regulative activities (e.g., monitoring) in developing TPACK compared to the low performers. Higher TPACK performers are more goal-oriented, demonstrate more monitoring and are more iterative in using all SRL processes in contrast to low performers who only partially regulate their problem solving. Such findings support previous research. This study adopts a novel approach for understanding the relations between SRL and TPACK. It offers opportunities to examine how teachers enact SRL as they move from the beginning to later stages of designing lessons and provides insights to researchers who study SRL in TPACK domains. Furthermore, the findings can assist educational designers in developing interventions for promoting TPACK development by concentrating on teachers' SRL abilities.

Keywords: self-regulated learning, TPACK, process mining, log files

Process Analysis of Teachers' Self-Regulated Learning Patterns in Technological Pedagogical Content Knowledge Development

Self-regulated learning (SRL) is an essential concept in the field of educational psychology. The notion is derived from research on metacognition and discusses how learners deploy metacognitive knowledge and skills to monitor and regulate their cognitive, motivational, and behavioral processes in learning (Pintrich, 2000; Winne & Hadwin, 1998). SRL has a pervasive, predictable, and instrumental effect on learning. Successful SRL enables students to engage in a recursive cycle of analyzing task conditions, constructing goals, monitoring learning strategies, and evaluating the effectiveness of the strategies (Azevedo & Cromley, 2004; Mega et al., 2014). However, dysregulation hampers learning, including failures to update one's standards and adapt to the demands of the task, deploy effective strategies, as well as make accurate judgments of one's progress (Azevedo & Feyzi-Behnagh, 2011). Such findings have been documented in research conducted across disciplines such as science (Deekens et al., 2018), mathematics (Kramarski & Friedman, 2014), medicine (Lajoie et al., 2014), and psychology (Sonnenberg & Bannert, 2015).

In the context of teacher technology education, technological pedagogical content knowledge (TPACK, Mishra & Koehler, 2006) plays a crucial role in teachers' effective uses of educational technology for teaching. It serves as a heuristic conceptual framework instructing teachers on how to combine their extensive technological knowledge with their content and pedagogical knowledge in an effort to make abstract subject topics more concrete and to assist students in constructing new knowledge (Mishra & Koehler, 2006). However, developing TPACK is complex in that teachers need to consider students’ specific needs as well as the constraints of learning contexts when performing technology-integrated practices (Angeli & Valanides, 2009).

Investigations into the relations between SRL and learning in TPACK commences with Kramarski et al.’s (2009, 2010) study wherein three metacognitive prompts were provided to student teachers during different phases of learning TPACK in a web-based context. Their findings demonstrate that participants obtained higher TPACK comprehension and performance of lesson design with SRL scaffolds in the planning and evaluation phases. In a study of TPACK in secondary in-service teachers Chen and Jiang (2019) found that teachers' SRL capacities play a different role in building TPACK, with planning capacity as the factor that exerts an exceptional influence. Poitras (Poitras et al., 2017; Poitras & Fazeli, 2016) contributes to this field of research by including a computer-based learning environment (CBLE) that is designed to facilitate teachers' SRL and TPACK. Poitras, Fazeli, and Mayne (2018) built a structural model to test several information seeking and acquisition behaviours (e.g., site visits using a CBLE), as predictors for TPACK, assuming that teachers who regulated their information seeking and acquisition behaviours could result in better TPACK performance. Another study using this CBLE analyzed preservice teachers' lesson plans and corroborates the arguments that teachers with high SRL abilities outperform those with lower SRL in terms of TPACK achievements (Huang et al., 2020). Despite significant findings, further examinations of the relations between SRL and TPACK are needed.

There is necessity to probe further into teachers' self-regulatory processes to establish a sound understanding of the relations between SRL and TPACK. The underlying assumption is that SRL is temporal and dynamic in the way it changes over time and in different contexts (Taub et al., 2018). Deeper insight into how SRL is performed can provide opportunities to explain why teachers succeed or fail in learning about TPACK. Studies looking into teachers' SRL processes in TPACK is still somewhat limited in the existing literature. Accordingly, the present study aims to fill this gap through modeling teachers' self-regulatory processes as they conduct a technology-infused task and will present inferences about the relations between SRL and TPACK temporally. The findings will provide insights as to how teachers enact SRL as they move from the beginning to later stages of designing lessons and provides insights to researchers who study SRL in TPACK domains. Furthermore, the findings can assist educational designers in developing interventions for promoting TPACK development by concentrating on teachers' SRL abilities.

Theoretical Background and Literature Review

Self-Regulated Learning

Several scholars have modeled students' SRL with different theoretical perspectives, such as the social-cognitive model of SRL (Zimmerman, 2002), the general framework of SRL (Pintrich, 2000), and the information-processing model of SRL (Winne & Hadwin, 1998). Despite differences, there are some commonly shared assumptions (Panadero, 2017; Puustinen & Pulkkinen, 2001). First, SRL is a constructive cyclical process consisting of phases. The first phase is forethought wherein students analyze the task or the problem to be addressed to understand available resources and the constraints for problem-solving. In the second stage of planning, students construct several specific learning goals, retrieve possible strategies, and select the most appropriate ones used for problem-solving. The next phase involves task execution, in which students monitor the enactment of the planned strategies and evaluate their consequences on learning. When learning is accomplished, learners in the last phase of self-regulation reflect on their performance and make modifications in general, which exerts influence in future learning. The second characteristic shared by all models is that SRL is assumed to be goal-oriented (Pintrich, 2000; Winne & Hadwin, 1998). Goals articulately indicate the expected consequences that guide how to regulate learning (Winne, 2001). When students develop clear goals, they are able to retrieve relevant prior knowledge appropriate for the tasks to be addressed and implement effective strategies to approach the objectives. More importantly, goals define the standards for metacognitive monitoring activities that contrast the products of a given SRL phase against the standards to determine whether or not the content should be restudied (Winne, 2001, 2010). In addition, researchers also emphasize the critical role of metacognitive activities in SRL and their effects on individual regulatory phases. Metacognitive activities consist of monitoring and control (Azevedo et al., 2012; Pintrich, 2000; Winne, 2001). Monitoring enables students to self-observe the entire study process, compare the achieved outcomes against their goals that have been set before learning, and identify whether or not differences exist (Winne & Hadwin, 1998). The internal feedback, accompanied by monitoring, leads to control activities that allow for refining task perceptions, adjusting objectives, or revising learning tactics and strategies (Schunk, 2008). As Zimmerman (1986) stated, “self-regulated learners are persons who plan, organize, self-instruct, self-monitor, and self-evaluate at various stages during the learning process” (p. 308).

Winne claims that metacognitive activities can take place during any phase of a regulatory process, allowing learners to control their study as needed (Puustinen & Pulkkinen, 2001; Winne & Hadwin, 1998). Hence, SRL is described as a goal-oriented process with distinguishable phases, but there is no assumption that these phases are arranged in a strict time ordered sequence (Azevedo, 2009; Bannert et al., 2014). In the exploratory research, Schoor et al. (Schoor & Bannert, 2012) demonstrated students' regulated learning over time by means of a process graph. They found that students processed a typical regulatory process of coordination, working on the task, and monitoring, which is different from what they expected from SRL models, i.e., working on the task – monitoring – coordination – working on the task.

Capturing SRL Processes with Logs and Process Mining Techniques

Since an SRL process is recursive and temporal in terms of real-time occurrence of regulatory events (Bernacki, 2018), it is essential to capture SRL with a novel event-based approach rather than self-reports that only examines SRL as an aptitude (Veenman, 2011, Winne & Perry, 2000). Recent research suggests event-based SRL measures treat SRL as a sequence of temporal events (Azevedo et al., 2012; Greene et al., 2011, Winne & Perry, 2000). Event measures require a learning environment that integrates advanced technologies to track and log students' actual, real-time events (Greene & Azevedo, 2010; Greene et al., 2019; Schraw, 2007). As such, computer logs can be extracted and analyzed to make inferences regarding SRL (Cho & Yoo, 2017; Winne, 2010; Zhou & Winne, 2012). According to Winne (2010), logs are defined as a collection of observable behaviors indicative of students' mental models that students apply to process information. The underlying assumption is that students do not perform

SRL randomly, so the logged behavioral data can account for systematic regulatory patterns (Winne, 2010). Log data are objective, do not rely on participants' perceptions or recalls, and cannot be calibrated by participants (Siadaty et al., 2016). Furthermore, a log encompasses multiple forms of information, such as when and where an event is enacted, how long an event is, or what sequence an event is in. Such information, hence, allows researchers to identify students' learning trajectories and make inferences about students' SRL processes in an accurate way (Bernacki, 2018; Biswas et al., 2014; Cho & Yoo, 2017; Winne, 2017; Zhou & Winne, 2012).

With log events, researchers are able to discover cyclical and temporal self-regulatory processes. Recent literature has shown that process mining (PM) can reveal specific features and sequences of SRL processes (Bannert et al., 2014; Reimann et al., 2014). PM works on time-stamped event logs, identifying, confirming, or extending process models to extract process-related patterns (van der Aalst, 2012). Since theories have assumed event-like SRL, the goal of PM is to present the expression of a sequence of log events generated by a particular SRL process. For instance, Bannert et al. (2014) differentiated the SRL process of academically successful and less successful students with events extracted from students' think-aloud protocols. Cerezo, Bogarín, Esteban, and Romero (2019) applied PM for SRL assessment in e-learning and found students who passed followed the logic of a successful self-regulated learning process. Sonnenberg and Bannert (2015, 2019) applied PM algorithms to test the long-term effects of metacognitive prompts on learning. Their findings reveal that the designed prompts had significant long-term effects on increasing the frequency of using metacognitive strategies. Additionally, PM outputs graphs comprising nodes and edges between nodes. By manipulating parameter threshold values of nodes or edges, researchers are able to deal with noise in the data, control the level of detail, and focus on the main relations among log events (van der Aalst, 2012). Thus, process mining has implications for understanding the temporal nature of SRL more fully.

Research on SRL TPACK development

Technological Pedagogical Content Knowledge

TPACK refers to teachers' effective use of technology for teaching and learning purposes. TPACK is often discussed as an extension of Shulman's (1986) construct of pedagogical content knowledge (PCK) by incorporating technological knowledge. TPACK accounts for seven sub-domains of knowledge (Mishra & Koehler, 2006). Content knowledge indicates how teachers understand the facts, structures, and difficulty levels of content. Pedagogical knowledge indicates what knowledge of general instructional principles and strategies teachers master. Technological knowledge represents teachers' technological skills (e.g., operations of tools and troubleshooting). PCK concerns teaching specific subject topics with domain-specific instructional methods. Technological content knowledge (TCK) refers to how teachers take the difficulty level of topics or concepts into account when deciding technology. Technological pedagogical knowledge (TPK) refers to how teachers adapt general technological and pedagogical skills to the characteristics of concrete subject topics as well as knowledge of learners and contexts. TPACK is a unique body of knowledge, meaning that it goes beyond mere integration of the individual knowledge domains towards transforming knowledge of sub-domains to a particular understanding of the values of technology for particular topics that are difficult to be understood by learners or difficult to be represented by teachers (Angeli & Valanides, 2009). This transformation requires cognitive and metacognitive activities needed to construct sophisticated TPACK by integrating knowledge across each knowledge domain (Krauskopf et al., 2015). These high-order thinking activities are of significance since they signify a teacher's deep understanding of identification, selection, or infusion of technology teaching purposes (Graham et al., 2012).

SRL in TPACK Development

SRL models pave the way for revisiting TPACK development by providing a framework that sheds comprehensive insight into the cognitive and metacognitive processes involved in the TPACK context. Empirical research conducted by Kramarski et al. (2009, 2010) has aligned learning about TPACK with three SRL phases of planning, actions, and performance, evaluation. Similarly, Poitras et al. (2017) conceptualized teachers' information seeking behaviors in performing TPACK tasks as planning, monitoring, and strategy use phases. Such research indicates that at different stages of TPACK learning there are specific activities relevant to SRL within each phase. Accordingly, we support a TPACK framework with three phrases. Teachers in Phase 1 analyze the task to be performed in the initial phase, to understand the task requirements in detail, and retrieve relevant prior knowledge from long-term memory. Phase 2 is the planning stage, in which teachers formulate concrete goals they would like to attain. Goals are critical for TPACK development because, according to SRL theories, goals can be transferred into standards guiding teachers' enactment of TPACK and evaluations of their TPACK efforts. What is worth emphasizing is that teachers in this phase attempt to transform independent sub-domain knowledge into the knowledge of the intersecting sub-domains, such as technological content knowledge. Phase 3 is TPACK enactment—teachers perfect their technology strategies by considering more factors. Monitoring plays a significant role in this phase, assessing the discrepancies between existing technology solutions and planned ones, or between the plausibility of proposed strategies and the possibilities of implementing these strategies in authentic teaching environments. Teachers draw on the feedback of monitoring to determine whether they need to refine TPACK enactment. Throughout the entire developmental process, TPACK is also used as metaknowledge for evaluations and reflections; for example, whether additional knowledge of a particular technological tool is needed for decisions.

Descriptions of Study and Research Questions

This study aimed to answer the research question regarding what SRL process patterns can be identified while teachers are developing TPACK. To gain a better understanding of the role of SRL in TPACK, we mined two types of process patterns. First, we classified teachers into three profiles indicating different levels of TPACK achievements. Under such a circumstance, we mined three SRL processes, known as global process patterns. Second, we selected the higher- and lower-performers from each TPACK profile and subsequently mined within-group process patterns, i.e., three SRL processes of the higher TPACK performers versus three SRL processes of the lower TPACK performers. Hence, we address two specific research questions: (1) what global SRL process patterns can be identified in terms of different levels of TPACK achievements? (2) what within-group SRL process patterns can be identified in terms of the high and the low TPACK performers with individual TPACK groups?

Methods

Participants

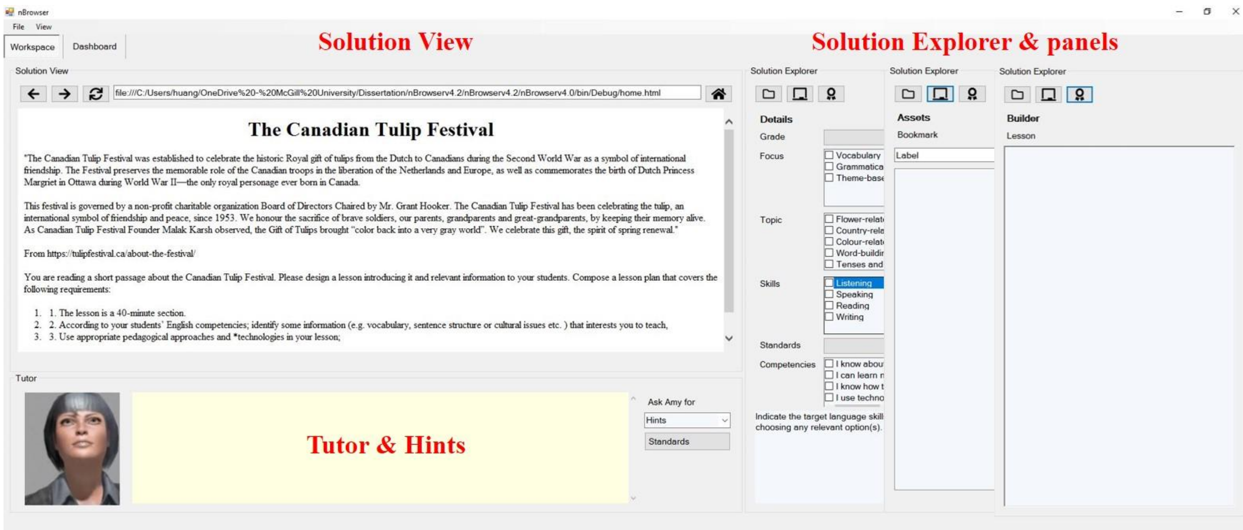
The participants in this study were 70 English as second language teachers in a city in the southern region of China. Of them, 49 student teachers (third-year university students), were recruited in a local normal university after we received the approval from the faculty administration and received the Ethics approval from the authors' affiliated university. Participants' personal information was treated in strict confidence. The in-service teachers were working at local public primary schools or higher institutions. The eligibility for participation was that potential participants had taken courses or training relevant to instructional pedagogy and technology. The mean age of the sample was 23 years old (*SD* = 6.96). The average teaching experience was reported as four years (*SD* = 5.94). Participants of the study were compensated 50 Chinese Yuan (equal to 10 Canadian dollars) for their time. Due to technical issues, three participants whose recordings were incomplete were excluded from the dataset, resulting in 67 participants' data used in the analyses.

Learning Environment and tasks

The nBrowser (Poitras et al., 2017) is a CBLE for TPACK development, and it provides teachers with opportunities to acquire and transfer TPACK into practice through designing a technology-integrated lesson. The system (Figure 6) involves two interfaces, namely, a Workspace and a Dashboard. The Workspace has three sections. The Solution View consists of a display of the learning material and online search tools. The Tutor section is placed underneath the Solution View, providing hints and a “TESOL Technology Standards Framework.” There are four hints in response to problems teachers might ask while solving the task. For instance, teachers might refer to the first hint if they did not have a clear understanding of what technology integration is. Also, teachers could use the second hint to get access to a website that offers numerous resources regarding educational technologies and exemplary scenarios. The Standards could assist teachers in reflecting on their performance of designing a technology-infused English lesson. On the left side is the Solution Explorer allowing teachers to analyze the task (the Details panel), seek online information and save online resources (the Assets panel), as well as edit and revise a lesson plan (the Builder panel). The dashboard presents teachers' learning activities and their outcomes. For example, the check teaching focus or the lesson plan exhibited in the dashboard. Teachers are able to switch between each interface freely to monitor their task solving process and make any modifications wherever they are necessary. Teachers click the "Save" button on the dashboard to save their work and indicate the completion of the task. All of the teachers' actions within nBrowser, such as clicks and movements, websites search, and lesson plans, were recorded in the log files. In this study, the participants were to design a technology-infused lesson with the provided material that introduces the Canadian Tulip Festival. Their lesson plans serve as one indicator of TPACK achievements.

Figure 6.

Interfaces of nBrowser



Procedure

The study was laboratory-based and participants were run individually. The day before the implementation, the experimenter emailed participants, enclosing an instruction video of nBrowser, the demographic survey, and the TPACK questionnaires. On the day of implementation, the experimenter asked participants to sign the consent form and fill in the survey and questionnaires, after which they were briefed on the objectives and the procedures of the study. Participants worked on nBrowser, analyzing the assigned tasks, performing online information searching, and completed a lesson plan within 45 min. The experimenter stayed in the lab throughout the entire process and did not communicate with participants except for technical issues. The experimenter alerted participants when there was 5 min remaining to complete the task.

Data Sources

Perceived TPACK Comprehension

The TPACK-practical survey (Yeh et al., 2014, Appendix C) was administered to examine teachers' self-perceptions of their TPACK competence. The survey includes 22 items rated on a 7-point Likert scale with 1 indicating “not at all true of me” to 7 indicating “very true of you.” TPACK-Practical assesses how teachers apply technologies to teaching from the following five pedagogical dimensions, i.e., knowing learners (3 items), Subject content (2 items), Curriculum design (8 items), Practical teaching (6 items), and Assessment (3 items). Yeh and her team developed the survey through the Delphi approach, inviting 60 researchers and specialists to evaluate the original scale in two rounds. According to their report, 95.83% of the items were considered critical components for the TPACK measurement (Yeh et al., 2014). Moreover, experts conducted two-rounds of evaluations, and the correlations of items in each round were between 0.5 and 0.73, which leads to robust validity to this survey (Yeh et al., 2014). In this study, the reliability (Cronbach's alphas) of the overall scale was 0.95, and the reliability of individual dimensions ranged from 0.78 to 0.91, which indicates a reliable measurement (George & Mallery, 2001).

Evaluations of Lesson Plans

Lesson plans were used to reveal teachers' ability to apply TPACK in their lesson designs. Lesson plans were retrieved from nBrowser logs. We assessed lesson plans based on six TPACK basic elements, namely, content, pedagogy, technology, PCK, TCK, and TPK. The evaluation rubric (Appendix D) was created by synthesizing three well-developed evaluation criteria, including Technology Integration Assessment Rubric (Harris, Grandgenett, & Hofer, 2010), the TPACK performance assessment instrument (Akyuz, 2018), and the TPACK lesson plan coding scheme (Janssen & Lazonder, 2016). The scale was 0–3 on each dimension. Participants gained a score of 3 points indicating an adaptive level when they considered students' characteristics and learning contexts into the TPACK framework. The score of 2 points denoted a specific level, meaning that participants presented details of information relevant to TPACK but indicated less consideration of students' needs. Participants received 1 point when they generally discuss individual TPACK elements in their designs. When there was no mention or unclear information of the TPACK elements 0 points were allocated. As a consequence, the maximum score for a single plan was 18. The higher score denoted more expert design skills relating to TPACK. Three evaluators collaboratively completed the work through a two-step evaluation. The first step was to establish the inter-rater agreement. Three researchers independently graded 25 lesson plans and compared their scores. The interclass correlation analysis coefficient was 0.86, yielding an acceptable agreement (Cicchetti, 1994). The second step included evaluated the remaining lesson plans. Three evaluators discussed and resolved all their differences. The first author made the final decision when agreements could not be resolved on a given evaluation element.

Identification of SRL Events

A process analysis of the computer logs collected from nBrowser was conducted (An excerpt is presented in Appendix E). In order to generate fine-grained SRL events, we followed trace-based, microanalytic measure protocols (Siadaty et al., 2016) that define the targeted SRL event list based on the theory and mapped the raw logs onto the SRL list. For example, goal setting is defined as constructing specific goals relevant to the task. The nBrowser provides a checklist that helps teachers clarify what their instructional goals are as they plan their lesson design. For instance, when the logs table shows "Lesson_Details_Topic_Checked," we mapped it onto the Goal setting category. Another example is Goal setting, which is related to three raw events of

"Lesson_Details_Focus_Checked," "Lesson_Details_Standard," and "Lesson_Details_LanguageSkills_Checked." The details are presented in Table 6.

Table 6

Reference Table for Defining SRL Events

SRL Event	Behavioural Indicators	Raw Logs
Task analysis	Check on Grade menu	Lesson_Details_Grade
	Check Technological Competencies box	Lesson_Details_TechCompetence_Checked
Goal setting	Check items in Focus	Lesson_Details_Focus_Checked
	Check items in Topic	Lesson_Details_Topic_Checked
	Check items in Skill	Lesson_Details_LanguageSkills_Checked
	Clicking on Standards menu	Lesson_Details_Standard
Search	Search / Navigation	Assets_URL Navigation_Bookmark Navigation_Event Navigation_Forward Navigation_Back
Transfer	Assign tags and Save as a Bookmark	Assets_Label
Reflection	Read Evaluation Criteria	Lesson_Plan_Evaluation_Criteria
Monitor	Requesting Hints to understand what technology integration means	Technology_Hint

Analysis and Results

Creation of TPACK Groups

TPACK groups were created prior to answering the research questions. These groups were associated with the levels of TPACK achievements that were predicted by the scores of the self-report of TPACK and the results of evaluations of lesson plans. The descriptive statistics demonstrated that the average score of perceived TPACK was 4.51 out of 7 (*SD* = 0.89) and around half of the sample obtained scores above the mean. In light of the results of the evaluations of lesson plans, the mean score was 7.60 out of 18 (SD = 3.18). The minimum score was 2, while the maximum was 18. For classification, hierarchical clustering (HC) analysis was performed using the R package. HC analysis is a frequently used method in data mining for establishing a hierarchy of clusters (Muntaner et al., 2012). The agglomerative HC algorithm was used to compute the dissimilarity of two pairs of observations by distance measure (e.g., Euclidean distance) and cluster data points internally coherent into a hierarchical tree-like dendrogram (Gil-Garcia, Badia-Contelles, & Pons-Porrata, 2006). We also employed the average silhouette method to determine the optimal number of cluster k (Kaufman & Rousseeuw, 1990). As a consequence, the dendrogram visualization (Figure. 7, Left) suggests that three clusters are optimal and the silhouette graph (Figure. 7, Right) confirms the output, which further presents the three distinct clusters with the involved members. Then we computed the mean scores of the TPACK survey and the evaluations of lesson plans in response to the three clusters. Based on our previous argument, proficiency in TPACK requires an understanding of TPACK, but more importantly how to apply TPACK for task accomplishments. Consequently, we labeled the clusters from least to best TPACK understanding as the knowledge-merit group (KMG), the competent group (CG) and the design merit group (DMG). As Table 7 exhibits, the largest group has the lowest level of TPACK, revealing 36 participants in the KMG category who had the highest scores in the TPACK survey but could not apply their understanding. The DMG (*n* = 16) included teachers who received a higher score in lesson plan evaluations but lower scores in self-reported TPACK. The DMG represented a medium level of TPACK. The third group, CG (*n* = 15), is characterized by the higher scores in both self-reports and the design task.

Figure 7

Dendrogram of the Clustering Result on TPACK Profiles

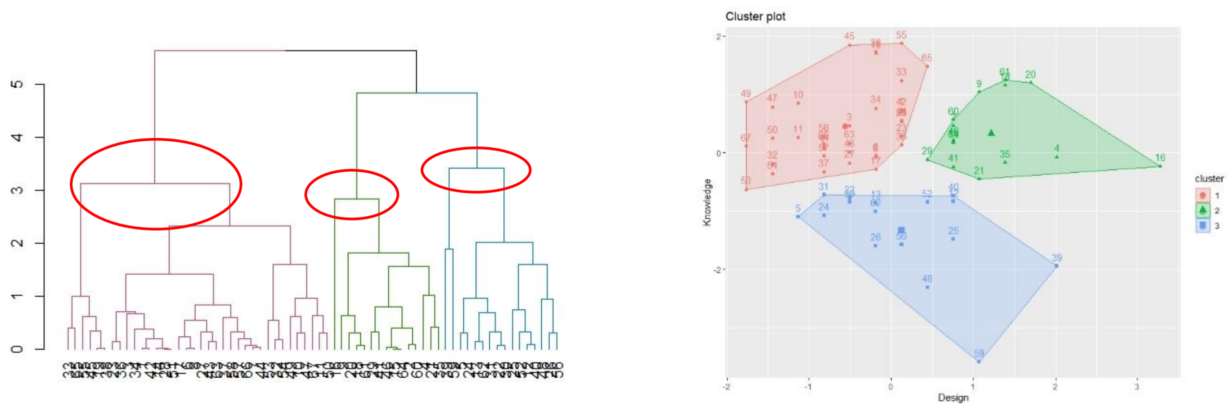


Table 7

Number of Members, Means, and Standard Deviations of SR Dimensions in Classes

Groups	N (%)	TPACK comprehension*	Design performance*
KMG	36 (53.7%)	4.92 (.58)/7	5.81 (2.05)/18
DMG	16 (23.9%)	3.33 (.68)/7	8.00 (2.63)/18
CG	15 (22.4%)	4.81 (.52)/7	11.47 (2.26)/18

Descriptions of SRL Events

Table 8 presents the statistical analysis of the identified SRL events, namely Analysis, Goal setting, Monitoring, Reflection, Search, and Transfer. In total, all SRL events were performed 3141 times. Search (*n* = 2125) was the event most frequently enacted in the KMG (*n* = 1292), the DMG (*n* = 392), and the CG (*n* = 441) while the events of Transfer, Monitoring, and Reflection were less performed. The events of Goal setting and Analysis were fairly enacted within each group. We also ran the one-way ANOVA test to see whether there is any difference between groups in terms of the counts of SRL events, and the results indicate no statistically significant differences can be detected on individual SRL events, with all *p* values greater than 0.05.

Process Analysis of Teachers' SRL

The analysis was conducted with RapidMiner Studio 9.7 and the ProM extension developed by the University of Eindhoven. Fuzzy Miner algorithm was applied to capture teachers' self-regulatory processes in the context of TPACK development. Fuzzy miner holds the potential to deal with unstructured events data and place such data into interpretable models (Günther & van der Aalst, 2007). Fuzzy miner visualizes event clusters by means of nodes and measures the level of importance of observed events via significance. There are three types of representations of nodes, namely, the highly significant nodes, clustered nodes that refer to the less significant but highly correlated ones and removed nodes that indicated the less significant and lowly correlated events. The edges in the fuzzy miner indicate the relations of two event clusters, which is reflected by the significance and correlation of edges. For fuzzy mining analysis, this study followed the default metrics setting, with the edge cut-off value of 0.2, and the significance cut-off of the node of 0 to examine how each event

Table 8

Counts, means and the ANOVA test of all SRL events for three groups

SRL	**KMG**			**DMG**			**CG**			**ANOVA**
	N	**M**	**SD**	**N**	**M**	**SD**	**N**	**M**	**SD**	
GS	278	7.72	2.3	111	7.25	3.44	116	7.4	2.75	$p > .05$
ANA	143	3.97	2.35	66	3	2.03	48	4.4	2.85	
SEA	1292	35.89	34.69	392	27.56	26.17	441	26.13	15.38	
TRA	83	2.31	3.09	28	1.56	1.83	25	1.87	1.81	
MON	38	1.06	1.51	20	1.63	1.82	26	1.33	1.92	
REF	15	.42	.73	10	.67	1.05	9	.56	.96	

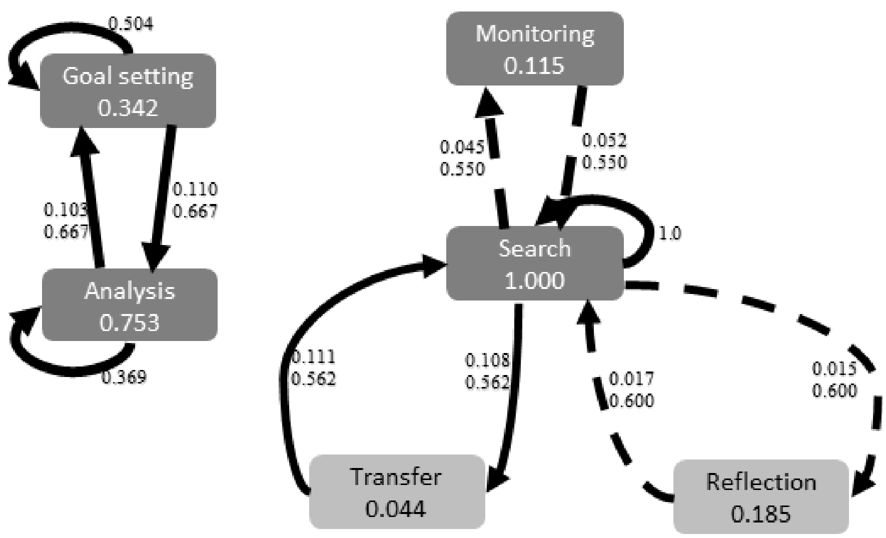
Note: GS = Goal setting; ANA = Analysis; SEA = Search; TRA = Transfer; MON = Monitoring; REF = Reflection was positioned in a process. In addition, we removed the Edit from the event list due to its higher frequency caused by the fact that nBrowser recorded every single keystroke as an Edit event when participants were writing lesson plans. Excessive counts did not provide meaningful information which resulted in using only six event types to analyze teachers' SRL processes. Using the PM methods, we will discover the global SRL processes and the within-group SRL processes. The global SRL processes capture teachers' regulatory patterns in relation to the general classifications of TPACK levels (low, medium, high). In contrast, the within-group SRL processes show sequential patterns for the best and worst performing members in a particular TPACK cluster, which provides opportunities to further detect how high achievers differ from low achievers as they orient, monitor, and evaluate the task as they develop TPACK. We will interpret the identified patterns based on the importance of nodes and relatedness of two nodes.

Analysis of Global SRL Process Patterns

Figure. 8-10 represent the process models for the three distinct TPACK groups. For the low TPACK achievements of KMG (Figure 8), the model shows two separate SRL routes. The more common route consisted of Monitoring, Search, Reflection, and Transfer. Based on the significance level of the nodes, Search showed the highest frequency, while Transfer had the lowest frequency. Monitoring had a similar significance level to Reflection. This means that Search, Monitoring, and Reflection events were frequently observed while participants were conducting design tasks. Furthermore, the edges of the nodes of this pattern demonstrated that Search and Transfer were significantly connected. Although the connections were identified between Search and Monitoring and Reflection, respectively, such connections were considered less significant and weak. Goal setting and Analysis were two significant events frequently performed by KMG participants. They were strongly connected with each other and produced another sequential path that was independent of the common one. Moreover, Search, Goal setting, and Analysis were self-looped, suggesting that participants enacted these events consecutively and multiple times in a row.

Figure 8

The SRL Process Model of the KMG

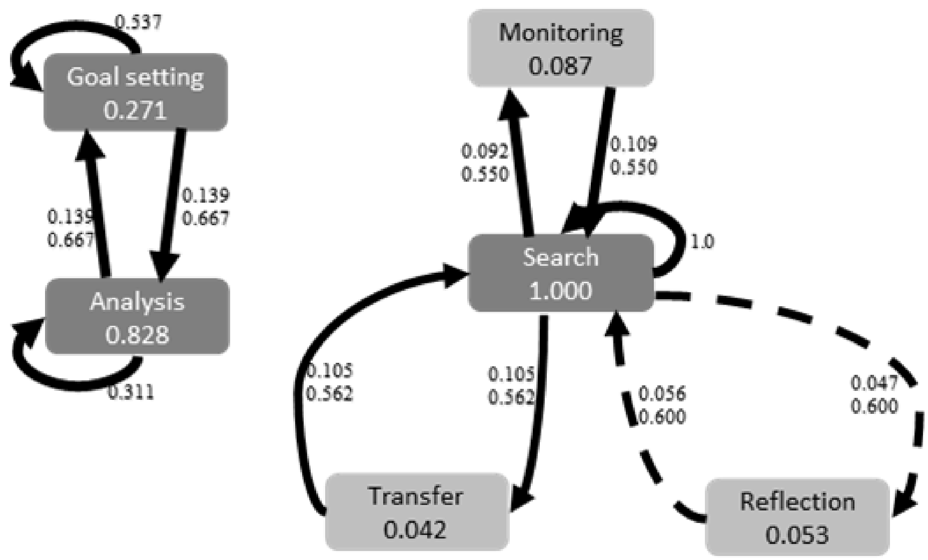


Interestingly, the DMG (i.e., the medium TPACK achievements) (Figure 9) shows a similar procedural graph to the KMG (lowest TPACK achievement). Two separate paths can be identified in this group. One consists of Monitoring, Search, Transfer, and Reflection, and the other includes Goal setting and Analysis. With respect to the connections Goal setting and Analysis are significantly and closely connected with each other similarly to the KMG. The loop between Search and Transfer was strong whereas the loop between Search and Reflection was weak. The degree of connection between

Monitoring and Search was stronger for the DMG group then the KMG, although the Monitoring event was less frequently observed as evidenced by its decreased significance level.

Figure 9

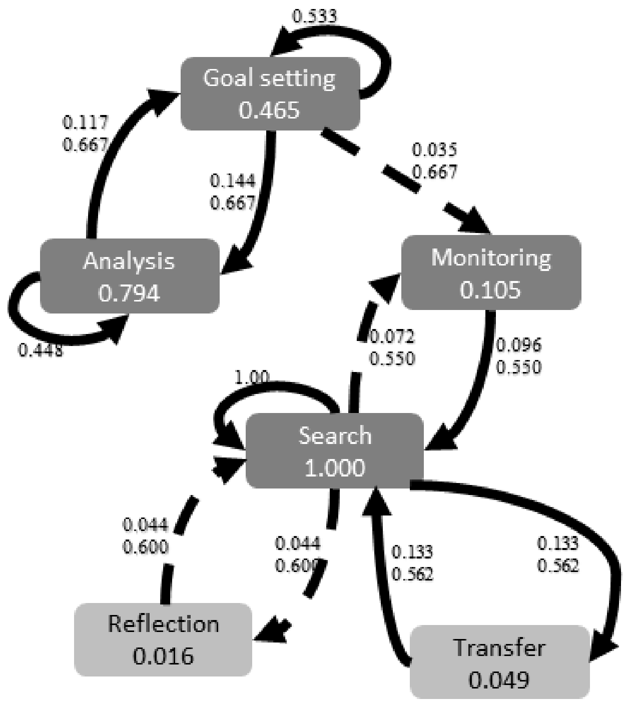
The SRL Process Model of the DMG



The model (Figure 10) of the CG representing the high TPACK achievements exhibited a different sequential pattern. All SRL events in this model were connected in a direct or an indirect way. All events except Reflection and Transfer showed high frequency. Participants started with Analysis and Goal setting, which led to a loop among Monitoring, Search, and Transfer. This sequence suggests that participants constantly monitored their searches of online information and evaluated their usefulness before saving them as available resources for lesson edits. Search also led to Reflection, but the connection was weak, which might be due to the low occurrence of Reflection (low significance level). Similar to the other two groups, Analysis, Goal setting, and Search were enacted multiple times in a row, evidenced by the self-loops.

Figure 10

The SRL Process Model of the CG



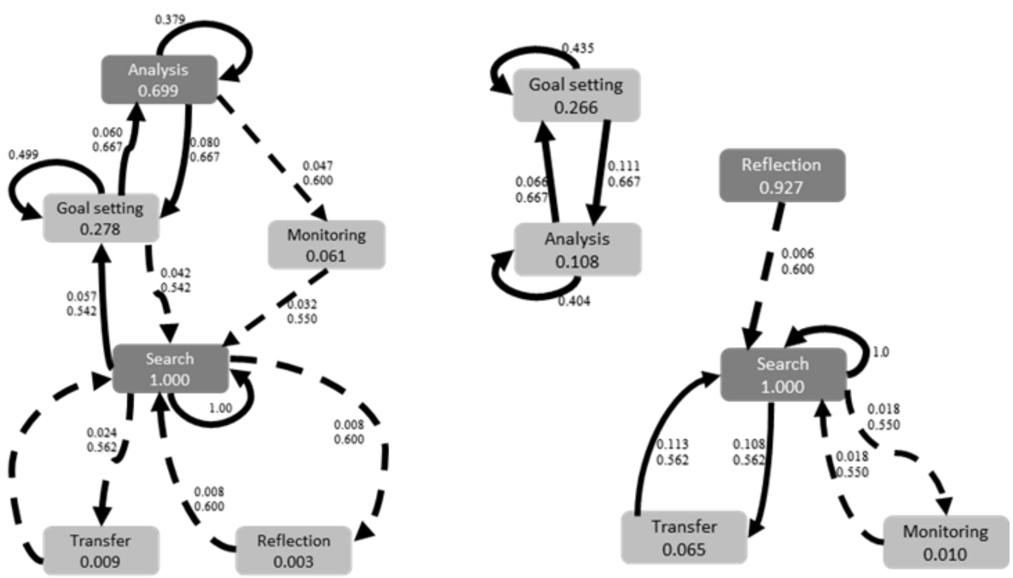
Analysis of SRL Processes within Groups

In addition to the global analysis, we further conducted a within-group analysis of SRL processes. Within each identified TPACK cluster, we further created a higher-performing sub-cluster (high cluster) that reflects the participants' TPACK achievements (top 5 participants) and a lower-performing sub-cluster (ranked last 5 of the entire group). The resulted six process graphs were presented in Figure 11-13. Within the KMG, the process map of the high cluster (Figure. 11a) showed an iteratively sequential model. Participants frequently performed SRL actions of Analysis, Goal setting, Search given the high significance of events. With respect to transitions, the model began with a loop of Analysis, Goal setting, Search, and Monitoring and then led to Reflection or Transfer. Although all events in this pattern were connected, there were only two transitions at a relatively high significance, namely, the mutual connections between

Analysis and Goal setting as well as the transition from Search to Goal setting. In contrast, the low cluster (Figure. 11b) showed a different process that was similar to the process map of the global SRL process of the KMG. Goal setting and Analysis were in a strong mutual connection, but neither of them connected with other SRL events. Search in this model played a central position, connecting with Reflection, Monitoring, and Transfer. The most significant nodes were Search and Reflection, meaning that the participants spend more time searching online information and self-reflecting lesson plans according to the TPACK standards. Moreover, it has been noticed that, despite differences, Analysis and Search were the two events that obtained a higher significance level in both process patterns.

Figure 11

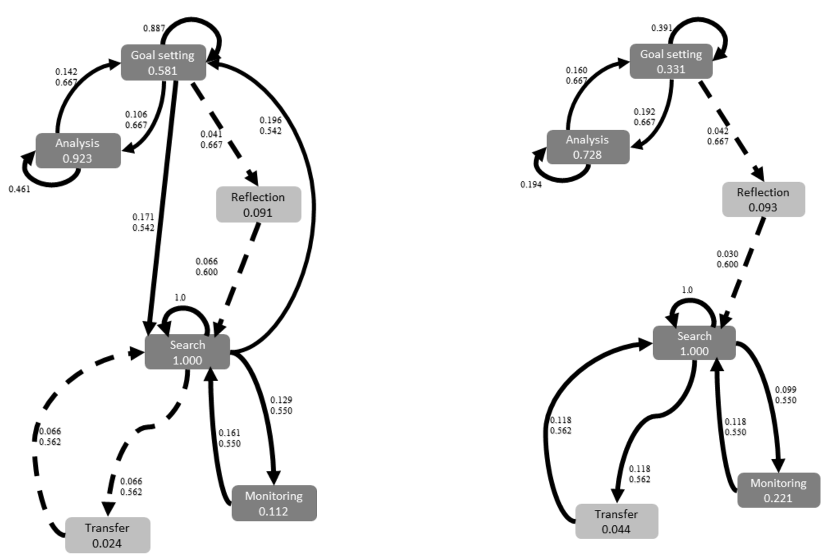
The SRL Process Model of the High Cluster (11a, Left) and the Low Cluster (11b, Right) in the KMG.



The two process maps of the DMG are displayed in Figure. 12a (the high cluster) and 12b (the low cluster). The regulatory process model of the high cluster exhibits more of an iterative pattern than that of the low cluster. The high performing participants circled within Goal setting – Reflection – Search, which suggests that the Search was goal-oriented and reflected. Analysis - Goal setting - Search – Monitoring composed a meaningful transition. In a sense, these loops could consolidate that participants performed self-regulation oriented by goals and in a nonlinear way. By contrast, low performing participants regulated their task solving through transition of Analysis - Goal setting – Reflection - Search – Monitoring/Transfer. Compared with the model of the high cluster, this process was goal -oriented but in a more linear way. The significant connection between Search and Monitoring reveals that the event of Search was monitored. The significant connection between Search and Transfer reveals that the participants might save numerous online resources for lesson designing. Different from patterns of the KMG, the most significant SRL events existing in both models are Search, Analysis, and Goal setting and Monitoring.

Figure 12

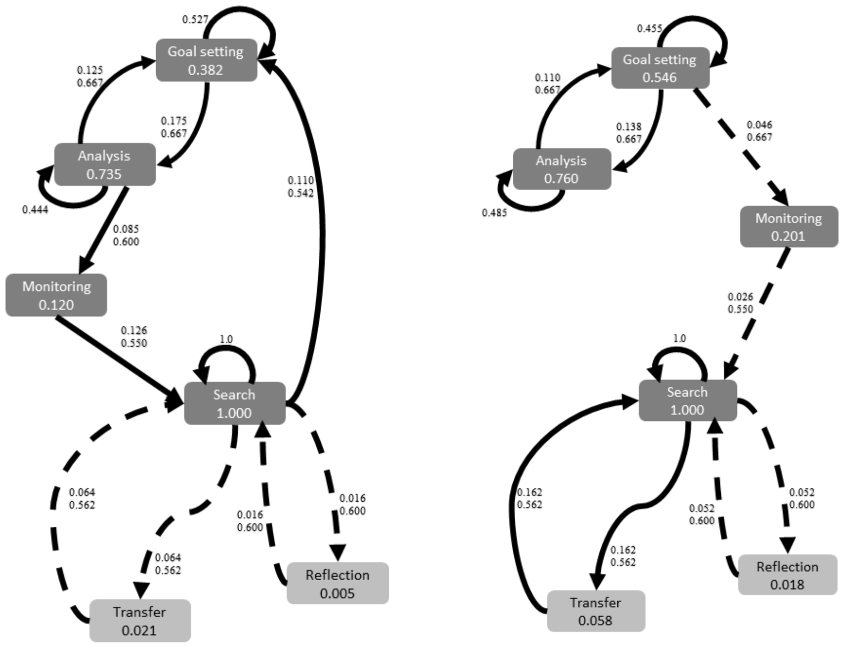
The SRL Process Model of the High Cluster (12a, left) and the Low Cluster (12b, right) in the DMG.



Within the CG, participants in the high cluster (Figure. 13a) started their lesson design from constructing instructional goals and proceeded to analyze conditions like students and self-evaluation of technological competencies. After that, they monitored their search actions, which includes looking for external online resources provided by nBrowser or reading sample lesson plans. The action of Search was then connected to Goal setting, which might suggest that participants modified their instructional goals, and a new circle began. This is a major route in this SRL process, revealing a successful self-regulative pattern. Either Transfer or Reflection was followed by Search, forming two independent minor loops. However, the two minor loops were displayed by dash lines because their significant values of correlations were small, indicating weak connections. The process model for the low cluster (Figure. 13b) was goal-oriented in a sense because it started with the loop of Analysis and Goal setting, followed by Monitoring, Search, Reflection, or Transfer. However, there were only two significant connections, Analysis - Goal setting and Search – Transfer. Compared with the process of the higher cluster, this procedural pattern of the low cluster is more linear. Participants might complete their lesson design tasks with fewer considerations of updating or modifying other regulatory actions. In both graphs, Search, Analysis, and Goal setting and Monitoring reached a higher significance level, indicating frequent exposures to these actions.

Figure 13

The SRL Process Model of The High Cluster (13a, Left) and The Low Cluster (13b, Right) in the CG



Discussion

The purpose of this study was to explore the patterns of teachers' SRL processes in the context of TPACK development. Previous empirical research consistently emphasizes that SRL mediates learning outcomes, with higher SRL associating with better achievements (e.g., Huang et al., 2020; Kramarski & Michalsky, 2010). Thus, the present study measured teachers' TPACK achievements by assessing their TPACK understandings and lesson plan and lesson designing performance, which leads to three levels of TPACK achievements, namely, the competent group (CG), the design-merit group (DMG), and the knowledge-merit group (KMG). Since TPACK is conceptualized as knowledge for accomplishing authentic tasks rather than the integration of sub-domain knowledge (e.g., CK, TCK), we defined CG as representing the highest level of achievements since it involved both knowledge and transfer of knowledge to an actual lesson design. The DMG and the KMG indicated the medium and the low level of TPACK achievements respectively. In this context, we endeavoured to discover the patterns pertaining to teachers' SRL processes via PM methods. The identified global SRL process patterns and the within-group SRL process patterns generally reveal that teachers' SRL processes vary based on different levels of TPACK performance. To elaborate on the variations and differences, we will discuss the findings in detail in the following sections concentrating on 3 aspects of SRL, namely whether teachers' SRL processes are goal-oriented, whether the SRL processes are iterative, and how the SRL processes are monitored.

Were Teachers' SRL Processes Goal-Oriented?

Contemporary SRL models acknowledge that the self-regulative learning process is goal-oriented (e.g., Pintrich, 2000) and that goal setting activities usually occur in the initial or before learning phase. Goals help establish various specific standards that allow learners to activate self-evaluations for learning performance (Schunk, 1990). Without clearly-defined goals, learners will have difficulties in planning strategies, monitoring learning, and defining success and failure. Our findings support the fact that teachers who are learning to integrate technology into their lesson plans are goal oriented. The most frequently noted SRL processes in these teachers were goal-oriented events, evidenced by the significant occurrence of the Goal setting event at the beginning of an SRL process. Teachers constructed specific instructional goals and oriented their lesson design activities accordingly. Specifically, teachers used goals to orient analysis of students' characteristics, manifested in the high connections between Goal setting and Analysis found in all models. Furthermore, the Search event was followed by Goal setting in most observed SRL models, which suggests goal-oriented searches of online resources of possible technologies was a frequent event. In addition, connections between Goal events and Monitoring in regulatory patterns were identified in the high TPACK achievement groups identified in the competent and the medium knowledge group. These sequences illustrate that high performing teachers could be adjusting goals according to the consequences of monitoring their search results. However, we do acknowledge that the CBLE (i.e., nBrowser) helps support goal setting through its interface since it provides a feature for teachers to define specific instructional goals. That is to say, every participant establishes a goal before proceeding to conducting online information seeking and transfer. However, participants can revisit and revise goals as many times as they like.

Were Teachers' SRL Processes Iterative?

SRL theory hypothesizes that successful learners frequently enact metacognitive monitoring activities that evaluate the consequences of different phases and update the conditions for operating the next phase (Sedrakyan et al., 2016; Winne, 2001). Hence, the SRL process is characterized by a tendency to work in an iterative rather than a linear way. The resulting models of this study support this hypothesis. Teachers with higher TPACK achievements exhibited iterative SRL processes whereas lower achievers did not. For example, the global patterns of the CG and the DMG suggested that teachers were able to adaptively perform metacognitive monitoring activities to analyze their searches and evaluated them before deciding to save them as useful resources for technology-infused instructions. By comparison, the regulatory process of the KMG is observed as a non-iterative approach manifested in limited monitoring activities enactment throughout the lesson design process. In light of the within-group patterns, the high clusters of each group demonstrated iterative SRL sequential patterns. The monitoring event played a pivotal role in leading teachers to constantly assess the performance of other SRL events such as Goal setting, Analysis, or the Search of technological solutions. The low performing clusters of the competent and design group showed a slight tendency to regulate their lesson designing in an iterative manner because iterative approaches were manifested by some significant mutual connections like Goal setting and Analysis. However, the low performers of the knowledge group failed to present an iterative SRL pattern.

How were teachers' SRL processes monitored?

SRL models place a high emphasis on metacognitive monitoring activities since they are pivotal in enabling learners to constantly evaluate consequences produced in different SRL phases and are needed to determine necessary modifications (e.g., Azevedo et al., 2012). As we see in this study, the process models illustrate that in general teachers who exhibited better TPACK achievements executed more monitoring activities and made more efforts to monitor other SRL events. For instance, monitoring events in the CG showed a higher significance level and were observed to have significant connections with the events of Search, Transfer, and Reflection. Similarly, the high TPACK performers in the DMG and CG actively utilized Monitor to assess events such as Goal setting, Search, or Analysis. Teachers with lower TPACK achievements also enact monitoring activities. However, their efforts to monitor were limited, and the entire self-regulative process was partially monitored, in contrast to higher achievers. Kramarski and Michalsky (2010) used metacognitive self-questioning (one type of monitoring techniques) to facilitate preservice teachers' TPACK development. The results of their study illustrate that metacognitive monitoring could enhance preservice teachers' ability to regulate their learning processes, which, in turn, benefits their TPACK. Although we adopted a different approach to investigating the role of metacognitive monitoring activities, our results are considered in line with what empirical studies have found and consolidate the assumption that metacognitive monitoring is central in the self-regulation of learning leads to higher performance.

Limitations and Future Directions

Log trace data are subject to being challenged in terms of interpretability and accuracy, although trace-based measure protocols (Siadaty et al., 2016) offer optimal solutions about how to translate raw traces into fine-grained SRL events. The multichannel data and multimodal learning analytics still have to be adopted in future research (Azevedo & Gašević, 2019; Worsley & Blikstein, 2015). Moreover, Fuzzy Miner only builds descriptive models that benefit model development but do not directly relate to statistical testing. The conformance checker algorithm (Rozinat & van der Aalst, 2008) of PM can be applied to test the goodness of fit of the model. In addition, the obtained patterns might be specific for the teaching scenario and the participants (i.e., English teachers), and consequently, generalizations of the resulting patterns should be used with caution. Future research should consider various contexts and samples. In addition, the use of nBrowser might intervene with teachers' SRL process as the nBrowser is designed based on SRL models, highlighting phases of goal setting, strategy enacting, and reflection. We did not examine whether or not teachers show changes in SRL over time. Future research can determine this issue by using experimental designs using control and intervention groups or pre and post-tests to minimize the impacts of learning environments.

Conclusion

In conclusion, this study identified SRL sequential patterns, a novel approach to inspecting the relations between teachers' self-regulation and their TPACK development. Although this study is exploratory rather than predictive, we did establish specific regulatory procedural patterns that are generally in line with what previous studies (Chen & Jang, 2019; Kramarski & Michalsky, 2010; Poitras et al., 2018) have indicated which is that high performers are more likely to adaptively perform self-regulative activities in knowledge acquisition to ensure better learning consequences.

Despite limitations, we do believe that the present study has scientific and practical implications. While educators are seeking effective ways to measure TPACK, the lens of SRL offers insights into teachers' enactment of regulatory activities in addressing authentic instructional tasks. In doing so, educators can understand how teachers rationalize their selection and implementation of technologies and transform their technological knowledge into complicated knowledge domains such as technological pedagogical knowledge. In the context of becoming more expert-like in TPACK performance the findings of this study suggest that expert teachers should be self-regulated, adaptive in deploying technological strategies for teaching and learning problems and evaluating the effectiveness of strategies to guarantee outstanding performances. Most of the previous research on TPACK largely focuses on evaluating the effectiveness of training programs. Examining teachers' SRL abilities, in particular the metacognitive elements in the context of TPACK, has received insufficient empirical investigation. This study lends supports to the demands that SRL should be incorporated into teachers' professional training, whereby cognitive and metacognitive regulation should become part of teachers' repertoire when they are accomplishing instructional tasks (Kramarski and Kohen, 2017, Michalsky & Kramarski, 2015). We see the advancement of developing teachers' TPACK in CBLEs as a promising approach to provide guidance and intervention to promote teachers’ SRL in specific contexts. Using advanced technologies can serve as both a research and training platform to advance TPACK scholarship (Poitras et al., 2017).

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Appendix C

TPACK-Practical Survey

Part 1: Before you begin, please tell us about yourself.

1. Age (in years): _______
2. Sex (F or M or Others): _______
3. Are you a(n)
    a. student teacher
    b. in-service teacher
4. Do you graduate from a normal school/university?
    a. Yes
    b. No
5. Degrees you are doing/have obtained
    a. Undergraduate
    b. Bachelor
    c. Graduate
    d. Master
    e. PhD
6. Teaching experiences (in years): _______
7. Your students are
    a. Primary students
    b. Junior middle school students
    c. Senior middle school students
    d. Post-secondary institutes

Part 2: TPACK Survey

Please indicate how well each statement describes you.
If a statement is very true of you, circle 7.
If a statement is not at all true of you, circle 1.
If a statement is more or less true of you, circle the number between 2 and 6 that best describes you.

1. Know how to use technology to know more about students.	1	2	3	4	5	6	7
2. Know how to use technology to identify students' learning difficulties.	1	2	3	4	5	6	7
3. Be able to use different technology-infused instruction to assist students with different learning characteristics.	1	2	3	4	5	6	7
4. Be able to use technology to better understand the subject content.	1	2	3	4	5	6	7
5. Be able to identify the subject topics that can be better presented with technology.	1	2	3	4	5	6	7
6. Be able to evaluate factors which influence the planning of technology-infused curriculum.	1	2	3	4	5	6	7

7. Be able to design technology-infused lessons or curriculum.	1	2	3	4	5	6	7
8. Be able to identify what types of technology-infused curriculum designs can be used to solve teaching objectives difficult to achieve.	1	2	3	4	5	6	7
9. Select appropriate technology representations.	1	2	3	4	5	6	7
10. Use appropriate technology representations to present instructional content.	1	2	3	4	5	6	7
11. Be able to use appropriate technology representations to present instructional content.	1	2	3	4	5	6	7
12. Be able to indicate the strategies which are appropriate to be used with technology -integrated instruction.	1	2	3	4	5	6	7
13. Be able to apply appropriate teaching strategies in technology-integrated instruction.	1	2	3	4	5	6	7
14. Be able to indicate the advantages and disadvantages of technology on instructional management.	1	2	3	4	5	6	7
15. Be able to use technology to facilitate instructional management.	1	2	3	4	5	6	7
16. Be able to indicate the differences between the contexts of technology-infused teaching to the contexts of traditional teaching.	1	2	3	4	5	6	7
17. Be able to use technology to facilitate the achievement of teaching objectives.	1	2	3	4	5	6	7
18. Be able to indicate the influences of different technology to instruction.	1	2	3	4	5	6	7
19. Be able to indicate substitute plans for technology-infused instruction.	1	2	3	4	5	6	7
20. Know the types of technology-infused assessment approaches.	1	2	3	4	5	6	7
21. Be able to identify the differences between technology-integrated assessments to traditional assessments.	1	2	3	4	5	6	7
22. Be able to use technology to assess students' learning progress.	1	2	3	4	5	6	7

Appendix D

Evaluation criteria of participants' lesson plans

TPACK Elements	Not Applicable (0 point)	Low (1 point)	Medium (2 points)	Advanced (3 points)
Content	not stating the content or the presence of content is irrelevant to the teaching materials/curriculum	content is stated clearly but generally or board. *Example "teaching objectives: vocabulary"; "to have students understand the cultures";*	specify the topic-specific content or identify the difficult aspects of the subject content. *Example "teaching objectives: vocabulary: tulips; scarify, govern"; "difficulties: the past particle form of verbs in the passive voice";*	specify the concrete the topic-specific content or difficult aspects and elucidate that they are derived from the demand of students or curriculum *Example the lesson focuses on past particle form of a verb because students need to learn them for the use of passive voice.*
Pedagogy	not using or using only one method in the teaching	multiple pedagogical methods are used but stated in simple ways. *Example "skim and scan the passage";"let*	multiple pedagogical methods are stated clearly and the specifications of these methods are articulated *Example scan the material because it allows*	multiple pedagogical methods are specified, and and/or teachers know how they contribute to student-centered learning *Example*

		students work in groups";	*students to understand the main idea quickly. And perusing helps to find the details.*	*Task-based teaching is student-centered by which students can learn by perform tasks independently or collaboratively.*
Technology	not using any technology in teaching	one or more technologies are used but stated in simple ways. *Example* *"use computers, videos, and Internet";*	multiple pedagogical methods are mentioned clearly and the affordances and/or constraints of these tools are discussed. *Example* *"playing videos can stimulate students' interest"*	the specifications of technology are discussed in detail and/or teachers know how it contributes to student-centered learning. *Example* *"video can be used in the beginning to attract students' attention so that they might be more engaged in the lessons."*
PCK	no alignment between pedagogy and content, or the use of pedagogy is not aligned with content representation.	content information is stated generally and taught by simple methods, or content information is specified but represented by a single method;	subject/topic-specific contents are presented and multiple methods are used to support content representations *Example*	subject/topic-specific contents are presented and multiple methods are used to support content representations. And teachers use student-centered methods to encourage learning

		Example *"have students scan and the reading material to find out the main ideas and discuss with peers"*	*"I explain the structure of a passive-voiced sentence and ask students to find out all the passive-voiced sentences in the reading materials"*	*Example* *"Students first find out all the passive-voiced sentences in the reading materials and try to identify the general structure of such sentences through peer discussions. I will ask some students to share their opinions and make additional information";*
TCK	no alignment between technology and content, or the use of technology is not aligned with content representation	content information is stated generally and represented by a single technology; or content information is specified but represented by single technology; *Example* *"play a video about Canadian cultures"*	subject/topic-specific contents are presented and multiple technologies are used to support content representations. *Example* *"I will search additional information about Canadian tulip festival online and share it in the class discussion board. I also create a gap-fill game to help students*	subject/topic-specific contents are presented and multiple technologies are used to support content representations. And teachers encourage students' use of technology to present contents. *Example* *"students log in the class forum created by me and guess the flowers I uploaded*

		"show digital images of different types of tulips"	*understand the significance of such festival"*	*before. Then they complete a word puzzle game to know the names of the flowers."*
TPK	no alignment between pedagogy and pedagogy, or the use of technology is not aligned with pedagogical implementation	use a single technology to support teaching, or use a few technologies but teaching is designed simply. *Example* *"ask students to search online"* *"use a video and digital images in the warm-up session"*	teachers articulate how to use technologies to support their teaching in different stages of the class, but no consideration of after class or students' use. *Example* *"Scanning and skimming are important reading skills. I use a cellphone timer to count how much time students need to finish reading the material. I will also use a vocabulary game to engage students' word acquisition."*	teachers articulate how to use technologies to support their teaching in class, which includes using technologies in different stages and for different purpose, and /or the student use is encouraged. *Example* *"for collaborative work, I will create a class discussion board before the class in which I can assign students in groups with 3-4 people after their sign in."*

Note: PCK = Pedagogical content knowledge; TCK = Technological content knowledge; TPK = Technological pedagogical knowledge

Appendix E

The Excerpt of Log File Extracted from nBrowser

A	B	C	D	E	F	G	H
userID	eventI	eventTime			MouseLocation	eventType	Descriptor
20190519001'	'248'	'2019.05.19 10:09:43:1194'	'56443'	'0'	'Learning_Session'	'Timestamp'	'Start'
20190519001'	'249'	'2019.05.19 10:09:46:0613'	'56630'	'0'	'MouseLocation'	'Mouse_Enter'	'Browser_Navbar'
20190519001'	'250'	'2019.05.19 10:09:46:0773'	'56631'	'0'	'MouseLocation'	'Mouse_Leave'	'Browser_Navbar'
20190519001'	'251'	'2019.05.19 10:10:03:0833'	'57717'	'0'	'MouseLocation'	'Mouse_Enter'	'Browser_Window'
20190519001'	'252'	'2019.05.19 10:10:03:0952'	'57717'	'0'	'MouseLocation'	'Mouse_Leave'	'Browser_Window'
20190519001'	'253'	'2019.05.19 10:10:03:1002'	'57717'	'0'	'MouseLocation'	'Mouse_Enter'	'Browser_Navbar'
20190519001'	'254'	'2019.05.19 10:10:03:1052'	'57717'	'0'	'MouseLocation'	'Mouse_Leave'	'Browser_Navbar'
20190519001'	'255'	'2019.05.19 10:10:03:1224'	'57718'	'0'	'MouseLocation'	'Mouse_Enter'	'Browser_Navbar'
20190519001'	'256'	'2019.05.19 10:10:03:1324'	'57718'	'0'	'MouseLocation'	'Mouse_Leave'	'Browser_Navbar'
20190519001'	'257'	'2019.05.19 10:10:07:3019'	'57984'	'0'	'MouseLocation'	'Mouse_Enter'	'Browser_Window'
20190519001'	'258'	'2019.05.19 10:10:07:3099'	'57985'	'0'	'MouseLocation'	'Mouse_Leave'	'Browser_Window'
20190519001'	'259'	'2019.05.19 10:10:07:3524'	'57987'	'0'	'MouseLocation'	'Mouse_Enter'	'Browser_Navbar'
20190519001'	'260'	'2019.05.19 10:10:07:3575'	'57987'	'0'	'MouseLocation'	'Mouse_Leave'	'Browser_Navbar'
20190519001'	'261'	'2019.05.19 10:10:07:3628'	'57987'	'0'	'MouseLocation'	'Mouse_Enter'	'Browser_Window'
20190519001'	'262'	'2019.05.19 10:10:07:3708'	'57987'	'0'	'MouseLocation'	'Mouse_Leave'	'Browser_Window'
20190519001'	'263'	'2019.05.19 10:10:08:1660'	'58038'	'0'	'MouseLocation'	'Mouse_Enter'	'Browser_Navbar'
20190519001'	'264'	'2019.05.19 10:10:08:1734'	'58038'	'0'	'MouseLocation'	'Mouse_Leave'	'Browser_Navbar'
20190519001'	'265'	'2019.05.19 10:10:08:1942'	'58040'	'0'	'MouseLocation'	'Mouse_Enter'	'Browser_Window'

CHAPTER 5

Final Discussion

Summary

Much has been discussed regarding TPACK development in the literature on teacher technology education. It is well-acknowledged that teachers should achieve competency in using technology in their instructional practices to facilitate student needs and interests and to present complex abstract content in more concrete ways (Angeli & Valanides, 2009; Chai et al., 2012; Koh et al., 2017; Voogt et al., 2013). However, many teachers struggle with TPACK development. We know from the educational psychology literature that SRL plays an essential role in helping learners achieve deep learning and a higher performance. For this reason, it is important to study the relationship between SRL and TPACK development. A few studies have illustrated the general effect of SRL on TPACK learning (e.g., Kramarski & Michalsky, 2010; Poitras et al., 2018). However, this dissertation seeks to explore this relationship more fully by investigating the specific roles that specific SRL processes play in TPACK development. In particular, it explores teachers' active management of their own learning by examining the relationship that monitoring and controlling plays in using TPACK in practice to develop specific lessons.

This dissertation first fills in a gap in the literature by presenting a systematic review of the research on TPACK and the conceptual associations between teachers' SRL and TPACK. Chapter 2 presents a conceptual inquiry that provides both novel epistemological and methodological insights into TPACK. First, it redefines TPACK as knowledge that includes both declarative and procedural representations. Second, it discusses the developmental nature of TPACK learning as being stepwise in nature. Third, it situates the types of cognitive and metacognitive activities needed by teachers to self-regulate their learning about TPACK. The chapter concludes with methodological insights about possibly fostering TPACK in the context of TREs that can measure and scaffold SRL in a simultaneous manner. Chapter 2 proposes a new conceptualization of TPACK that includes a closer look at SRL that can be used to foster its development. Based on this conceptualization two empirical investigations are conducted to test the relationship between TPACK and SRL more closely.

Chapter 3 presents the first empirical study that investigates the relations between teachers' metacognitive activities and their TPACK development in a technology-supported instructional design task. Teachers are asked to create a technology-infused lesson plan in the context of nBrowser, a TRE. Analyses were conducted to examine the lesson plans. In particular, the study detected six metacognitive categories through analyzing participating teachers' lesson plans and identified two distinct SRL profiles using latent profile analysis. Findings indicated that teachers with a high SRL profile engaged more in metacognitive monitoring activities than the less competent self-regulated teachers in completing the task.

A second empirical study (Chapter 4) builds on chapter 3 and further examines how the SRL of the high TPACK performers differed from that of low TPACK performers. Process analysis of logs extracted from the TRE, that is the nBrowser, indicate that high TPACK performers were more likely to self-regulate TPACK development and their SRL processes were more goal-oriented and iterative and demonstrate more monitoring activities in contrast to low performers who only partially regulate their problem solving. Taken together, this work is of particularly significance within the domain of teacher technology education, given the findings presented above.

It addresses the gap in the literature and offers unique contributions to advance the field.

Contributions to the Community of Science

Contributions to Theory

Researchers have been working for several years to develop a coherent theoretical framework for TPACK that can lead to the effective promotion and use of technology in teaching. For several decades the TPACK community situated its theoretical roots in pedagogical content knowledge (Shulman, 1986) and produced meaningful perspectives accordingly. However, the framework has been criticized due to ambiguous definitions and fuzzy boundaries between knowledge of sub-domains (Angeli & Valanides, 2009; Archambault & Barnett, 2010; Cox & Graham, 2009; Jimoyiannis, 2010). This dissertation takes on the challenge of refining the TPACK framework by reconceptualizing TPACK as consisting of both declarative and procedural knowledge representations. The declarative aspects of TPACK refer to specific distinct knowledge that teachers are supposed to master for the sake of teaching with technology, for instance, knowledge of the benefits and challenges of organizing collaborative learning. The procedural form of TPACK requires teachers to apply acquired knowledge in practice to construct deep comprehension of TPACK and address instructional tasks in the real world. This new conceptualization is helpful for resolving the existing debate regarding whether TPACK is integrative or transformative. In addition, the reconceptualization of TPACK suggests that teachers' develop TPACK from a naïve stage (i.e., learning declarative TPACK) towards an advanced stage (using

TPACK as metaknowledge to complete tasks) (Angeli & Valanides, 2009; Cox & Graham, 2009; Kramarski & Michalsky, 2010; Krauskopf et al., 2015).

The second contribution to the theory is that this dissertation drew on SRL models and proposed the CoTMEC^{+} model to understand TPACK. The CoTMEC^{+} supports the transformative model and assumes four steps during the transformation: comprehending the task, transforming knowledge, monitoring and evaluating transformation, and constructing new comprehension. Furthermore, the model elaborates the cognitive and metacognitive processes essential for TPACK learning. The CoTMEC^{+} model constitutes a significant theoretical contribution to the current TPACK models. Krauskopf et al. (2015) argued that uncovering the specific processes underlying the TPACK transformation would benefit our understanding of how teachers manipulate single TPACK components in social situations and how they construct mental models that lead to deeper understandings of TPACK. The CoTMEC^{+} model also advances the field in that it can serve as an exemplar of what distinguishes expert technology-integrating teachers from novice teachers. Considering the lens of cognitive, affective, metacognitive, and motivational regulation(Azevedo et al., 2013), the CoTMEC^{+} also operationalizes TPACK learning as being mediated by teachers' use of strategies, self-beliefs, and affect. For example, novice technology integrators may be teachers who lack effective strategies for explaining their technology decisions or have low motivation to accept technology in their teaching. By contrast, expert technology integrators may have high technology efficacy and exhibit abilities to orient their actions with clear goals, making the most of their cognitive resources to monitor and control the technology integration to maximize the value of technology rich learning. Consequently, it is important to probe further into teachers' self-regulatory processes to establish a sound understanding of the relations between SRL and TPACK. In doing so, researchers can take advantage of SRL models to examine how teachers enact SRL as they move from the beginning to later stages of designing technology infused lessons. Prevalent theories within the TPACK literature often fail to specify cognitive operations used to assimilate information and develop a mental model for how a lesson will unfold. This dissertation addresses this gap in the literature by specifying the cognitive operations used to learn TPACK as teachers plan a lesson using technology. Furthermore, this research integrates SRL into the TPACK framework, which provides opportunities to consider other constructs like emotions and motivation, which is a significant complement in prevalent theories within the TPACK literature.

Contributions to Methodology

Contributing to the theory development of TPACK moves the field forward since it strengthens the framework as a common language and focus for productive discussion and knowledge creation (Ball, 2006; Graham, 2011; Wright, 2008). This dissertation also contributes to methodological designs. Scholars frequently use self-reports and observations to measure TPACK. However, teachers' mental processes of the perceptions of the task, the rationales for technology decisions, or the skills they deploy to solve constraints have been underestimated (Krauskopf et al., 2015). The current research demonstrates the benefits of assessing SRL involved in the TPACK learning process dynamically with trace data. Thanks to the advanced technologies, teachers' timely self-regulatory events can be captured when learning with TREs. Chapter 3 and Chapter 4 presented two different data types (i.e., lesson plans and log traces) used to analyze the online SRL processes. The SRL models of teacher performance were built using the computer log file data and subsequently these models had the predictive power to examine teachers' TPACK comprehension. Consequently, the innovative TPACK measurement, is advantageous as it informs researchers about specific levels of TPACK that can be observed along with additional factors that unfold and relate to the success of TPACK learning. Traditional measurement, i.e., static self-report questionnaires, does not reveal the changing nature of SRL processes or its influence of TPACK development. For example, Chapter 4 showed that teachers with lower TPACK levels scored poorly on implementing monitoring strategies that could influence better TPACK development. The new forms of measurement provided in this dissertation can tackle the issues pertaining to the gaps between self-reporting and performance (Willermark, 2018). Furthermore, such measures afford alternative approaches to understanding situated TPACK and providing intervention during the learning process (Poitras et al., 2017). The underlying assumption is that SRL is temporal and dynamic in the way it changes over time and in different contexts (Taub et al., 2018). Deeper insight into how SRL is performed can provide opportunities to explain why teachers succeed or fail in learning about TPACK.

Contributions to Practice

It is obvious from studies examining teacher technology education that the effective use of technology is a challenge for teachers working in technology-rich educational environments. Teachers often report the lack of cognitive resources and the limited opportunities to perform technology-integrated teaching practices (Ertmer, 1999), which hinders them from internalizing their understanding of TPACK. This dissertation makes practical implications for designing the technology education curriculum. First and foremost, the findings from this research strongly encourage fostering teachers to be self-regulated individuals who can proactively and capably monitor and evaluate their cognitive, metacognitive, motivational, and behavioral aspects of learning to cope with the constraints from the internal and external environment (Pintrich, 2000; Zimmerman, 2002). More specifically, SRL is domain specific and there is a significant benefit in linking teachers' SRL in the TPACK context helping teachers practice and allocate attentional resources to these important aspects of teaching (Moos & Pitton, 2014; Tondeur et al., 2012). SRL leads to active and deep learning, which helps teachers become more competent in specific situations. With the increasing number of advanced technology tools (e.g., VR devices, mobile applications) available for educational purposes there is no doubt that upgrading teachers' technology competencies along with their TPACK will need to become part of their daily teaching routines. Thus, the emphasis on SRL in TPACK training can equip teachers with lifelong learning skills to learn and implement novel and unfamiliar technologies. Second, fostering SRL in TPACK can also assist student learning about technology. Kramarski calls it teachers' dual self-regulation roles (Kramarski, 2017; Kramarski & Kohen, 2017). When teachers make efforts to regulate teaching with technologies, they also transfer SRL skills to their students and teach them how to leverage these skills to maximize the affordances of technology in learning about 21st-century skills.

Another outcome of this dissertation is the implication that integrating TREs into TPACK training is a useful educational direction. In this dissertation project, nBrowser was used as a TRE used for both research and training on TPACK. As an adaptive

TRE, nBrowser assists teachers in learning about the affordances of technologies by scaffolding their SRL efforts to seek and acquire information while navigating the web for online resources (Poitras et al., 2017). Results obtained from Chapter 3 and Chapter 4 evidenced that teachers with high SRL did outperform those who were less competent in SRL. Furthermore, nBrowser provides personalized learning experiences for teachers to enhance their TPACK competence. nBrowser holds the capacity to present diverse problem-based cases adapted from authentic teaching. It is vital for novice teachers to addresses these problems with nBrowser to gain rich experience of TPACK. In this way, teachers can build mental models that exhibit relations between TPACK elements and apply such mindsets in authentic teaching. Moreover, most TREs like nBrowser are informal learning environments, which can be integrated into formal technology education and professional development programs and complements existing TPACK interventions.

Limitations

The limitations of this dissertation stem from three sources. One limitation is research design. There was no pretest to measure teachers' SRL. The rationale for not administrating a pretest was to avoid familiarizing participants with the task to be addressed. However, the relationship between SRL and TPACK was confounded by the use of nBrowser that is designed as a tool to scaffold self-regulation during leasson planning (Poitras et al., 2017). For example, a teacher who is internally weak in SRL might demonstrate a high level of TPACK competencies in designing a technology-integrated lesson due to the support of the nBrowser. Such SRL could be temporary (Bannert et al., 2015) and could decrease if the external support fades out. Due to the lack of pretest data for comparisons, it is difficult to discriminate between the internalized SRL that may have been present before using nBrowser, from the SRL that may have been temporarily- acquired during nBrowser usage. Future research will address this issue by using pre-post tests of SRL. In addition, we examined TPACK in a laboratory based project with pre-service teachers. In future, we will look at how teachers use TPACK in classroom practice, and consider methods for developing a system that can provide a more comprehensive program for teacher professional development. Even seasoned teachers may struggle in making adaptations and therefore it is worthwhile to build a system to help all teachers with their TPACK development.

A second limitation of the research may reside in the grain-size of measurement. The current two empirical studies used online-trace methodologies to capture participants' deployment of SRL activities while learning with the nBrowser. Although such novel measures support assessing variables of interest, the validity of trace-based measures largely depends on the granularity. Put another say, it relates to how accurately the SRL events can be aligned with theory. Rovers et al. (2019) refers to the importance to the solid theoretical model and states that computerizing trace data will be meaningless without theory as behavioral measures may obscure mental operations. In this research, we adapted theoretical models from previous studies to define participants' SRL processes. However, it is possible that some SRL-related events were ambiguous and difficult to operationalize. For example, the activity of repeatedly browsing online information could be defined as monitoring contents or reviewing. Although the two regulatory activities are conceptually different, it is hard to discriminate simply based on behavioral indicators. Future research may use think-aloud data to provide further evidence of SRL and corroboration of SRL behavioral events.

Besides the above limitations, the role of SRL in TPACK development was only examined in two subject domains, math (Chapter 3) and English (Chapter 4), which limits the generalization of the findings across disciplines. SRL is domain-specific in nature (Poitras & Lajoie, 2013). We can not assume that the SRL skills teachers acquired from other learning contexts are perfectly transferred to learning about TPACK in new subject areas. Likewise, teachers from different disciplines illustrate distinct abilities to teach with technology (Cox & Graham, 2009). Therefore, in future, teachers' SRL abilities and TPACK practices will be examined in other disciplines.

Future Directions

We plan to improve our research findings by conducting additional series of studies to address the limitations discussed in the previous section. More specifically, future studies will utilize a different research design that incorporates pre and post-tests to assess SRL and TPACK in two task conditions (nBrowser vs. a regular condition). The factorial measurement will prevent confounding factors from the variables of interest. In doing so, we can gain a better understanding of teachers' SRL and its mediating and predicting effect on TPACK development. Secondly, further research will address the issues with respect to the SRL measurement. Translating raw log data to SRL-like events is critical for identifying the fine-grained SRL events from log files (Siadaty et al., 2016). In future, we can examine such log to consider the frequency and elapsed time of SRL activities to further determine the relationship between SRL and TPACK development. Moreover, we acknowledge that not all SRL activities can be indicated by means of log files. Future research should consider the identification of teachers' SRL with the collection of multiple data. For example, verbalized thinking and video recordings can be qualitatively coded to elucidate the specific cognitive and metacognitive processes that facilitate a conceptual understanding and the acquisition of sophisticated knowledge (e.g., Greene & Azevedo, 2009). Eye-tracking data offers gaze patterns and fixation behaviors on the areas of interest. With eye movement data, we can examine the attentional efforts learners allocate to specific self-regulatory events, and gain perhaps another lens on how teachers use their self-regulation (e.g., Taub et al., 2016) in a TPACK context. We suggest drawing on multimodal learning analytics (MLA) to converge multiple data sources to gain important insights into the learning trajectories and the internal state of learners (Spikol et al., 2017). In addition, our goal is to implement nBrowser in educational settings to facilitate teacher technology education. As an effective research and training platform, the nBrowser guides teachers to engage in SRL processes in completing TPACK tasks and collect data indicating teachers' self-regulatory behaviors (Poitras, et al., 2017). To optimize its effectiveness, our future work takes the direction in having more teachers working with the system to generate collective intelligences to increase the usability of the nBrowser. To this end, we need to develop more cases available for teachers regardless of disciplines and experience. This practice is particularly beneficial for novice teachers who can situate their learning about TPACK in authentic cases and gain practical experience (Angeli & Valanides, 2009). Given the benefits, we are confident that nBrowser serves as both research and training platforms to better understand the nature and development of SRL in the context of advancing future TPACK scholarship.

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