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Developing theoretical coherence in teaching and learning: case of neuroscience-framed learning study

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Abstract

Purpose – The purpose of this paper is to describe two cycles of learning study (LS) involving eight elementary teachers in British Columbia, Canada. The study explored the teachers' experiences of learning to plan and teach lessons as informed by recent brain research.

Design/methodology/approach – The case study was constructed using data sources including teacher semi-structured interviews (pre-study, post-study and delayed post-study), classroom materials (including student assignments), LS training materials, fieldnotes and recordings of meetings and research lessons; sources were triangulated. Thematic analysis was applied. Contemporary neuroscience perspectives framed the LS discourse and analysis.

Findings – The teachers developed theoretical coherence and could better articulate reasons for their pedagogy. They developed understandings of the cognitive architecture underlying functions like learning and memory, allowing them to identify pedagogical actions that are consistent with human biology and understand why these actions are effective in promoting learning.

Practical implications – LS is shown to be an effective professional development (PD) model where theoretical knowledge, like neuroscience, could be employed and tested in classroom settings to provide depth to support teachers' praxis. This teaching–research nexus supports exploration of fruitful connections between theoretical knowledge and education to advance the science of learning and the science of instruction.

Originality/value – Findings demonstrated how LS could be employed with alternative theoretical perspectives to promote teacher PD, thus extending beyond the dominant use of variation theory. Also, illustrated is the potential use of LS to bridge the knowledge gap between neuroscience and education.

Keywords Elementary education, Pedagogy, Professional development, Neuroscience, Learning study

Paper type Research paper

The benefits of teachers using theoretical knowledge to underpin their pedagogies are being acknowledged increasingly in learning study (LS) literature. This praxis serves to bridge the theory-practice gap, and to promote teacher and student learning (Martin and Towers, 2016; Pang and Lo, 2012). Recently, Runesson (2016) made explicit the need to separate the

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theoretical framework applied (predominantly, variation theory, Lo, 2012) from the LS approach. This would consequently make provisions for other theories to be fruitfully applied and examined within the LS contexts, which is currently a gap area in the literature.

Sharing the vision of extending the possibilities for teacher development within LS, the current study draws on neuroscience theories and research findings (e.g. Phelps, 2004; Shimamura, 2010) to provide teachers novel perspectives on learning and pedagogical tools. The study is designed to increase the accessibility of contemporary scientific research and knowledge to support teachers' pedagogy and their development of theoretical understandings of teaching practice; this constitutes a knowledge gap area and a common goal in the field of educational neuroscience (Goswami, 2006). Situated in British Columbia, Canada, where LS is mostly unfamiliar to teachers and teacher educators, this study appears to be the first LS case involving elementary school teachers in Canada. Two cycles of LS were implemented, where different groups of teachers worked with explicit neuroscience theories to develop and theorize about their pedagogy through collaborative classroom research (cf. Elliott, 2015). The findings focused on the teachers' experiences of learning to engage with neuroscience-framed instruction as part of their professional development (PD), where they tested pedagogical ideas in their classrooms. The following research question framed the study:

RQ1. What are the teachers' experiences of learning to integrate neuroscience with teaching practice?

Background literature: learning study, theoretical frameworks and neuroscience

Participating in LS has been associated with improvements in teaching practices (Wood and Sithamparam, 2015), teachers' knowledge (Nilsson and Vikström, 2015) and supporting teachers in developing and bringing together theoretical knowledge, research-based knowledge and content knowledge. As a result, teachers create an integrated understanding of the relationships between theory and practice (Pang and Lo, 2012; Vikström, 2014). Despite the rapidly expanding research, several aspects of LS remain relatively unexamined. For example, to date, LS explicitly and almost exclusively employs the same pedagogical theory – namely, variation theory (Lo, 2012; Marton and Runesson, 2015). Runesson (2016) contended that this is actually problematic for the development of LS and variation theory as the two have practically become synonyms for one another; variation theory can have applications outside of LS (i.e. Baillie *et al.*, 2013; Bussey *et al.*, *2013*) and LS must be open to other theories to broaden its scope and support its further development (cf. Martin and Towers, 2016).

Learning and pedagogical theories are relevant when engaging in PD because theories provide the lenses through which teachers understand various aspects of their professional practice (Tan, 2014b; Korthagen, 2010). These theoretical perspectives provide teachers with frameworks to understand and reflect on their teaching instruction, student learning and the relationships between their pedagogical decision making and student learning (Kullberg *et al.*, 2017). Underpinned by varied epistemologies, different theoretical understandings of knowledge have different implications in terms of how teachers interpret student learning and evaluate their pedagogical actions. Thus, despite the valuable insights offered by theoretical perspectives of teaching and learning, these lenses inherently limit how and what teachers see in their teaching practices (Lo, 2016). This catalyzes the need to explore diverse theoretical and pedagogical perspectives.

With regards to teachers' PD, LS responds to the need for the development of pedagogical theories that integrate theories of learning and teaching practices (Lo, 2012). This is because translating theoretical principles into educational contexts depends on engaging teachers in reflective practice that is open to testing, and developing learning and pedagogical theories (Elliott, 2015; Kullberg *et al.*, 2016). Martin and Towers' (2016) recent study further demonstrated how pedagogical principles of "folding back," as an alternative theoretical framework to variation theory, could be fruitfully explored for its effectiveness as a pedagogical tool and thus alludes to its potential to widen teachers' repertoire of theoretical lenses they could use to examine student learning.

When considering different theoretical frameworks to underpin LS activities, the rapidly advancing field of educational neuroscience – including new knowledge of the neural mechanisms underpinning cognitive processes and what those understandings can offer teaching – merits examination (Ansari *et al.*, 2012; Patten and Campbell, 2011). Within educational neuroscience, there is both support and caution against the translation of brain research to classroom instruction (Bruer, 2016; Goswami, 2006). Initially, skeptics argued that our understanding of neuroscience were too nascent to meaningfully inform education. Bruer (1997), for instance, claimed that the utility of neuroscience did not extend beyond reifying well-established theories in educational psychology. Moreover, many authors have highlighted that early, empirically driven brain imaging studies were rarely grounded by theoretically sound cognitive models. This led to *post hoc* explanations of how neural mechanisms directed cognitive processes, such as learning, and led to the propagation of many salient neuromyths (false but widely held beliefs about brain function) in education (Arsalidou and Pascual-Leone, 2016).

More recently, however, cognitive neuroscientists have demonstrated that studying the neural mechanisms underlying human cognition can extend and improve our understanding of learning. There is a growing recognition within educational neuroscience that it is inherently limiting to base instructional practices on psychological models that describe how the brain produces cognitive phenomena (i.e. learning and memory) at a level of abstraction that ignores the structure and physiology of the brain itself (Anderson, 2007; Mayer, 2017). However, there is a translational issue between educators and neuroscientists pertaining to how teachers speak the language of education and neuroscientists speak the language of science.

Within the field of educational neuroscience, it is widely recognized that teachers act as agents of change in education and, thus, the success of educational neuroscience hinges on teachers being able to effectively interpret, apply and report on educational applications of neuroscience (Fischer *et al.*, 2010). As such, education requires a mode of PD capable of building teachers' neuroscience fluency, which, as is argued below, LS can comprehensively fulfill. By extending the LS framework to include additional theoretical models, translational issues between educators and experts in parallel fields, such as neuroscience, could be resolved for the betterment of education as a whole.

Research design

Participants

Two cycles of LS, each lasting about five months, were implemented over two years as part of an elementary school's PD program. Participating teachers were selected based on their interest and availability. All the teachers have their teaching certification and have at least a bachelor's degree. They have approximately 1–5 years of experiences teaching their respective grade levels, with 2–20 years of overall teaching experiences. In the first cycle, five Grades 1–6 teachers participated in the LS. During lesson planning in the LS, the teachers were further grouped into lower and upper grade-level teams (Grades 1–3 and 4–6, respectively). Three Grade 2 teachers participated in the second cycle which was implemented a year after the first one.

Learning study

LS was deployed as the teachers' PD approach due to its distinctive characteristic of framing teachers' collaborative discourse using a theoretical framework and promoting teacher classroom research and reflection (Elliott, 2015; Pang and Lo, 2012). Studies have reported the effectiveness of LS in improving teaching and supporting teacher learning (e.g. Holmqvist, 2011). Using neuroscience theories to develop the theoretical framework (see next section), this study explored the phenomenon of teacher learning promoted through the LS context.

Tan and Nashon's (2013) LS framework was largely adapted (see Tan and Nashon, 2013 and Table I for details). Generally, the LS consisted of the following phases:

(1) Theory-framed lesson planning (planning phase).

(2) Iterative cycles of teaching among team members (iteration of research and reflection phases): research lessons were revised based on lesson observations, and individual and group reflection. Team members implemented the revisions in the next round of teaching.

(3) Sharing of insights with the professional community (dissemination phase).

Theoretical framework

Contemporary neuroscience research findings were distilled and used to frame the LS (see Table II), and thus deviated from the dominant use of variation theory in LS. Neuroscience theories were chosen based on the potential relevance to teaching practice (cf. Dubinsky *et al.*, 2013). The intention is to provide teachers with a theoretical understanding of human cognition that they can use to develop teaching strategies that are consistent with what is known about brain function and the ways students learn, rather than on specific applications of neuroscience in delivering specific content.

The neuroscience theories included the neural network hypothesis of learning and memory, which is a widely accepted theory of knowledge formation that proposes how a widely dispersed network of brain cells can be altered over periods of time through the process of synaptic plasticity (Kemp and Manahan-Vaughan, 2007; Pulvermüller, 1996); the network of cells contain the memory of an object or concept learned. The theory provides teachers an understanding that encountering a learning object entails activating a distinct network of brain cells that contain all of the sensory information associated with the object; the information can be referred to as event features, that is, features of learning events/experiences that the learner remembers (episodic memory). Connections within the network can be strengthened through revisiting the learning object, invoking more senses or attaching emotional significance; conversely, connections can also weaken (Caroni *et al.*, 2012). A strong network produces a robust mental representation of the learning object, which can be extended through further learning experiences.

Hierarchical relational binding theory (hRBT) was also employed in the study. The theory suggests that representations of learning objects are made up of smaller units of information (e.g. visual, auditory, sensory, affective) that are processed and stored in distinct areas in the brain. The stronger the connections between brain cells are in its network, that is, the more units of information are processed and retrieved, the greater the likelihood of recalling the learning object (Cabeza and St Jacques, 2007; Shimamura, 2010). This theory supports the teaching practice of previewing and reviewing concepts in order to reinforce neural connections.

The third set of neuroscience research findings employed relates to a learner's attention and awareness. Basically, the brain filters and prioritizes incoming sensory information. Emotions can help the brain to prioritize information that comes to the learner's attention and aid in recall (Phelps, 2004; Osaka *et al.*, 2013). Novelty, an element of newness or surprise, is another factor that determines if attention is directed toward a desired learning object (Horst *et al.*, 2011; Ranganath and Rainier, 2003). The degree of novelty in the new information should be balanced with setting instructional tasks at an appropriate level in

LS meetings	LS Cycles 1 and 2
Planning phase	
(1) Teachers identified the problem to be tackled (shared goal)	The point of departure was based on improving student learning, where teachers wanted to tackle teaching difficult topics in the newly implemented curricula in British Columbia After discussions which drew on the teachers' prior teaching experiences, the teachers decided to work on the following: summary and setting (language arts, Cycle 1); life cycles (science, Cycle 2)
(2) Teachers explored neuroscience information	Neural network hypothesis, hierarchical relational binding theory and the influence of emotions and novelty on attention were discussed; neuroscience articles (e.g. Shimamura, 2010) were read and discussed Cycle 1: 3 meetings, 3 h; Cycle 2: 5 meetings, 5 h
(3) Teachers collaboratively designed lessons (integrating neuroscience with teaching)	Consistent with neuroscience perspectives, teachers made use of probes to identify gaps in students' learning. The gaps also helped identify the object of learning and determined the event features that constituted the object of learning They then collaborated to design the lessons, reviewing their existing resources and creating new ones Cycle 1: 5 joint meetings (5 h), 3 split group meetings (total: 4 h); Cycle 2: 3 group meetings (3 h)
Classroom research phase[a]	
(4) Teachers taught their research lessons (average class size: 24)	Teachers taught the research lessons while the researchers and rest of the team members observed the lessons (either in person or via video-recordings) "Probes" and "check for understanding" activities (pre- and post-lesson tests) were used to assess student knowledge and ascertain student learning Lessons were revised based on reflection and feedback (see reflection phase) Team members implemented revisions in the next round of teaching. (Some teachers retaught their lessons.) Cycle 1: $n=10$ lessons (2 per teacher), total 8.5 h; Cycle 2: $n=6$ lessons (2 per teacher), total 6 h
Reflection phase[a]	
(5.1) Teachers reflected on their lessons	Teachers individually reflected on student learning and teaching practices by examining their own classroom data (e.g. probes, check for understanding activities, teaching materials and recordings of lessons)
(5.2) Teachers discussed lessons with researchers	Post-lesson conference with researchers (usually immediately after the lesson or within the same day); lessons discussed Cycle 1: $n=5$ (40 min–1 h each); Cycle 2: $n=3$ (40 min–1 h each)
(5.3) Teachers reflected as a group	Post-lesson conference with team members; teachers discussed their overall insights with team members. Video-recordings of lessons and classroom materials were used in the discussion Cycle 1: upper grade level: $n=2$, total 2 h; lower grade level: $n=1$, total 1 h Cycle 2: $n=2$, total 2 h
Dissemination phase	
(6) Teachers shared their experiences	Teachers shared their insights and learning experiences with their professional communities (via grade-level meetings, school presentations, workshop seminars)

Note: [a]Iterative cycles of teaching included both the classroom research and reflection phases

Table I. Learning study implemented

order for the new information to connect with existing features for that particular concept. Thus, it is important to constantly probe for students' knowledge in order to determine what could be novel and what features their existing networks might already contain.

Data sources and analyses

In order to capture the fullness of the teachers' LS experience, an interpretive case study approach was employed where different methods were combined and analyzed (Yin, 2003).

	Neural network hypothesis for memory and learning	Hierarchical relational binding theory	Attention and awareness
(1) Focus	Networks can be altered – synaptic plasticity (Pulvermüller, 1996). That is, teaching can physically alter brain structure	The hippocampus (part of the brain) is involved in recalling of concepts learned (Shimamura, 2010). Not all information are recalled with the same degree of clarity due to different neural mechanisms	The brain is a pattern recognition "machine" that prioritizes and selectively stores information
(2) Key idea	The brain turns experiences into memory; mental representations for distinct concepts are created through strengthening or weakening synaptic connections in dedicated network of brain cells (Pulvermüller, 1996)	To strengthen recall, the learner can extend neural networks based on new information/experiences (and thus learn)	Recognizable patterns can be created through balancing between the introduction of novel and familiar learning incidences (Ranganath and Rainier, 2003), as well as creating positive (or sometimes "negative") emotions (Phelps, 2004)
(3) Relationship with teaching instruction	Concepts are consolidated by strengthening neural pathways (Caroni *et al.*, 2012). Multi-modal and multisensory learning experiences are encouraged	New information must connect to existing networks, thus the importance of determining appropriate objects of learning, and the reviewing and reinforcing of concepts	It is important to systematically introduce key features of a concept Probing and pre-exposing students to concepts ahead of time are encouraged to increase familiarity of the learning object

Table II. Summary of theoretical neuroscience discussed in the learning study

Serving triangulation purposes (Lincoln and Guba, 1985), the multiple data sources included individual teacher semi-structured interviews (each lasting about an hour, transcribed verbatim), classroom materials (including student assignments), LS materials and meeting notes, researchers' notes and recordings of meetings and lessons (post-lesson conferences with researchers were also transcribed). The data stimulated recall and aided the construction of the overall LS discourse of which the authors situated the teachers' learning and instructional practices (see Table III).

Pre-study interviews ($n = 8$) explored the teachers' pedagogy and views of student learning. These were compared against the post-study interviews ($n = 8$) (implemented immediately after the corresponding LS cycle) that probed for the teachers' learning experiences, including their planning and teaching of neuroscience-framed lessons. During the interviews, the teachers referred to student assignments (evidence of student learning) and other classroom resources; these sources were analyzed accordingly. During the transition between the first and second LS cycle, delayed post-study interviews (after a year) were administered for the first group of teachers ($n = 3$); these interviews provided information about the aspects of neuroscience the teachers applied beyond the study. A comparison of the three sets of interviews (alongside other data sources) provided instances of teacher learning that the authors pursued in the analysis.

Thematic analysis as detailed in the study of Braun and Clarke (2006) was employed to construct themes that cut across the data set. Interview transcripts capturing the teachers' own accounts of their experiences were analyzed together with corresponding data sources that provided the context for the utterances. The initial inductive coding of the interview data, i.e., coding without trying to fit into a pre-existing frame, was implemented to identify patterns in phrases and meanings, and key instances of teacher learning.

Table III. Data sources and analysis

Analysis	Data sources	Notes
(1) Context and learning study discourse	LS meetings: video-recordings, notes on neuroscience (given to teachers), researcher's notes of meetings	Stimulated recall of the overall LS discourse the teachers participated in Helped locate teachers' description of their experiences (transcripts) within the learning study context
(2) Teaching practices	Video-recordings of lessons and meetings (including post-lesson conferences); lesson plans and classroom materials used; probes and check for understanding activities	Aided the description of the teachers' research lessons Lesson plans and classroom materials provided understandings of the teachers' thinking behind the use of neuroscience in their teaching Probes and check for understanding activities helped capture the students' learning, compared with teachers' comments about their lessons Teachers' lesson planning, enactment and evaluation (reflection) were compared against each other
(3) Teacher learning	Pre-study, post-study and delayed post-study interviews; recordings and transcripts (selected portions) of post-lesson conferences	The teachers' own learnings were analyzed by comparing transcripts of the three sets of interviews, as well as the post-lesson conferences Transcripts provided information on what neuroscience theories the teachers drew on to design and enact their lessons Transcripts were analyzed for how the teachers evaluated their own lessons and LS experiences, and learned Coded and themes were generated

Subsequently, a more deductive approach was employed where transcripts were marked and codes were collated based on selected lines of inquiry (e.g. slowing down lessons; role of event features; drawing on neuroscience information).

Three themes were constructed, where narratives and selected excerpts described the teachers' experiences of integrating neuroscience theories with their teaching practice. The themes were verified and refined by testing them against the data set. Individual analyses were scrutinized as a team (Stake, 1995), in order to increase reliability and develop a collective interpretation of the data set.

Findings

Developing theoretical understandings of "Slowing down" lessons – how students could learn

The teachers were keen to address teaching difficult parts of the newly implemented BC curriculum; enhancing student learning of these otherwise difficult topics constituted the point of departure of the LS. Teachers in the first LS cycle designed their objects of learning around students learning to write about a setting in a story (lower grade team) and a summary (upper grade team), while teachers from the second cycle focused on the science topic of life cycle.

Teachers in both groups developed theoretical understandings around the pedagogical act of "slowing down," where they would have otherwise covered the same content in a shorter period of time. However, the teachers' attention was not on the pacing of the lessons, but on how students could learn. As observed in the research lessons, the teachers explored multiple ways for students to learn the targeted concept. This was an idea emerging from the teachers' discussions of the importance of extending and reinforcing neural networks through adding more information and meaningful repetition, respectively (recording of meetings), as is consistent with the neural network hypothesis and hRBT.

For instance, Jolene had her Grade 2 students engaged in a group discussion matching the traits of a camel to reasons they are found in specific habitats (pre-exposure activity); the learning object was for students to connect traits of an organism in its particular stage of life cycle to its adaptation to the environment. As is observed in the videorecording (research lessons), the students watched a video of how octopus mimicked other organisms (e.g. stingray) to develop their understandings of adaptation. Jolene also made use of the iPad for students to digitally record their own narratives of the different stages of the frog life cycle. She then ascertained student learning via their assignments, which demonstrated their ability to describe the traits needed to help the frog survive, of which the students were able to correctly point out the frog's adaptations. During the post-lesson conference, Jolene drew on the neural network hypothesis to explain how the varied activities were designed to help extend students' neural connections, emphasizing "When you learn something, it engages different parts of the brain and not just one specific part, but multiple areas." In the interviews, she likewise theorized this teaching strategy as:

> (1) Jolene: I think I slowed down. I spent more time on one concept than I normally would. So ideally that's how teaching should be […] It made me think of lots of different ways to teach one concept […] I think just being able to teach it in lots of different ways helped.

The teachers also drew on the idea of synaptic plasticity, that is, neural connections in the brain can be physically altered, to support their use of different pedagogical strategies to teach the same concept (see excerpt below). The teachers were able to visualize how learning is connected to brain functioning, and based their pedagogical decisions on this understanding of neural mechanisms:

> (2) Jolene: It was interesting to see that when you review and taught something in many different ways, your brain actually physically changed. I never thought of that. We all knew that the more you teach, the more you review, it is gonna stay in your head. But I never thought that physically, your brain is being shaped.
>
> Interviewer: Is there any resource that helped deepen this understanding?
>
> Jolene: The article and your slide show of the actual brain […] Just seeing the brain and all the different coloured pathways, how all the networks connecting.

The teachers' theoretical understandings of "slowing down" also entailed ensuring that students learn the event features at each step of the teaching intervention. They paid close attention to how event features of the targeted concept (ascertained via pre-tests) were adequately previewed and reviewed before and after the lessons. As discussed in the LS meetings and found in the notes distributed to the teachers, these pedagogical acts promote the linking of new knowledge to existing neural connections where the new information is recognized by the brain –brain pattern recognition and filtering mechanism. According to the teachers, common practices like previewing and reviewing are given new significance in view of their profound effects on human cognition. This in turn provided the theoretical lens to examine student learning.

For example, Linda reflected on how her students were able to identify the habitats of animals, but were unable to connect that with the key concept of adaptation (how traits were suited for a particular environment):

> (3) Linda (post-lesson conference): They had trouble identifying what actually made the animal work in the habitat […] "Oh, we put the lion, the elephant, the giraffe, all in the grassland because I know they live in Africa." They had that sense, but couldn't really articulate what it was, why they live there.

As captured in the recording of the post-lesson conference, the team eventually attributed students' learning difficulty to a recent fieldtrip to a salmon cannery. Linda perceived that students "become obsessed with fishing and being sustainable, the environment and the impact of everything" (post-lesson conference excerpt). This provided an opportunity for the team to consider the importance of pre-exposing concepts to be taught: the post-lesson discussions included how Linda could have had students discuss habitat features as a previewing activity, where students would eventually link specific habitat features to traits of the organism. Equally important is the necessity to constantly review and check for students' understanding of event features (such as traits, habitats, different animals), in order to ensure that the event features (as new information) are located within students' existing neural networks.

The teachers pronounced and theorized seemingly simple pedagogical practices of previewing and reviewing concepts, as they observed the impacts of these practices on student learning. The insights teachers gained are illustrated in the excerpt below. Noteworthy is how teachers from the first LS cycle likewise deemed previewing and reviewing concepts as sound, theory-supported pedagogical strategies they used throughout the year (delayed post-study interviews):

> (4) Linda (post-study interview): The one big takeaway is how important it is to pre-teach and make sure that the kids had a really good working knowledge of what you're trying to do […] taking the time to really make sure that they have that [understanding] before you go on.

Increased clarity in the design of learning objects – what students could learn

The teachers approached the design of learning objects using neuroscience perspectives. In general, they learned to apply ideas around "event features," which refer to units of information that are stored in the brain and could be recalled (hRBT) to determine what students could learn; event features constitute both multiple sensory information and modalities used (neural network hypothesis). As captured in the meeting notes and recordings, the teachers began conceptualizing targeted concepts (learning objects) as comprising of event features, where designing a learning object would necessitate considering what event features are critical to students learning the concept at that particular grade level. The teachers further determined the appropriateness of the event features through probes (pre-tests) administered before the lesson to uncover students' knowledge.

This approach of lesson planning shifted the teachers' focal attention from pedagogical acts to considering what students are learning, as visualized through students forming and extending neural connections. The teachers spoke strongly of how determining and testing the event features (i.e. probing) increased the clarity of what students needed to know in order to form a robust mental representation of the concept, as noted in the example below:

> (5) Interviewer (post-lesson conference): How did knowing the event features ahead of time [through probing] affect lesson planning?
>
> Denise: I think I was really clear in the event features that they [students] had to know. They already knew what traits were and the life cycle, but not linking the two […] When we first started planning, it was already overwhelming. But having those event features and breaking it down in this way was really focused. "What do we want them to know at the end? How are we gonna test to see what they already know now?"

In the above excerpt, Denise described the initial planning experience as being overwhelming: it was noted how life cycles was a new topic in the recently revised science curriculum, and thus may be unfamiliar. Additionally, all the teachers in this LS team mentioned about facing challenges teaching science as elementary teachers (captured through the pre-study interviews). The apprehension to tackle the topic was apparent when they articulated their intentions of teaching the science topic using a social studies approach (fieldnotes).

They wanted to focus on the historical importance of salmon in British Columbia instead of the life cycle of salmon.

According to the teachers, approaching the learning object using the neuroscience idea of event features helped them to overcome anxieties of teaching difficult science topics. The teachers learned to break down the concept of biological adaptation to its event features. Noteworthy is how the teachers eventually taught what could be considered as complex biological concepts that are typically beyond a Grade 2 level. For example, instead of focusing on the stages of the life cycle, the teachers extended students' learning by exploring the sophisticated concept of linking the features of an organism in a particular stage of the cycle to its habitat. This was made possible through the extensive discussions of event features that spanned across three meetings.

Also of importance is how the teachers found their own ways to integrate the neuroscience term "event features" with teaching, which further demonstrated the theoretical work they engaged with. Apart from the practice of probing for students' existing knowledge, Denise devised her own way of turning event features into questions, akin to an integration of the underlying importance of both probing and determining appropriate event features for a learning object:

> (6) Denise (post-study interview): I have been trying to take the event features and make them into questions. And then if I think the answer to that question is "yes, they can do it", then that event feature is set. Maybe I have been kind of fusing the two ideas, having a set of questions and the event features.

What is illustrated above is how Denise combined the separate processes of determining the event features with that of designing probes. It has been noted that event features were introduced in the LS separately from the importance of probing. Event features emphasized the importance of building an extensive network (neural network hypothesis), while probing is underscored by the saliency of ensuring that new information is recognized and filtered by the brain (attention and awareness), where the information is subsequently added to the existing neural network for the concept. For the teachers, it has been found that the two theoretical perspectives were conflated in practice, thus suggesting their own interpretations and internalization of the neuroscience perspectives.

Drawing on the above notion of event features as diagnostic and reflective tools appeared to have lasting applications for the teachers. For example, Matt highlighted how the idea of event features changed the way he planned and taught his lessons throughout the year. Providing the example of essay writing, he explained:

> (7) Matt (delayed post-study interview): In the past, it has been established without why we are doing essay writing, and then we say what things have to be included […] Instead of saying, "you need to write an introduction or a thesis statement", "What is a thesis statement?" So we break down the event features: You need to know what the question is […] What is your point?

Matt strongly emphasized how the neuroscience information, particularly about event features, provided the theoretical support and lens for considering what students should focus on in their learning. He further theorized that event features are not something communicated by telling, but is explored through "break[ing] down the event features" into smaller components in teaching.

The thinking behind the teaching: articulating pedagogical decisions

By examining changes in the teachers' pedagogy, the first two themes alluded to the teachers' development of theoretical coherence in their practice through integrating neuroscience with their teaching. Further pursued in this thematic strand is the teachers' own introspection of how learning about neuroscience through LS provided a lens and the language to support their teaching practices, where they could now articulate their pedagogical decisions based on empirical scientific research. In this regard, Matt explained:

> (8) Matt (delayed post-study interview): The parts that stood out for me were the fact that different things were stored in different parts of the brain. And even [though] I knew that before, that all types of sensory information would be important […] The idea of the connections being made and being strong with the use of reinforcement seems very obvious. But, having the scientific information behind it, and how the brain works and stores those memories, just made it so that when I am planning those things, they are much more explicitly built in. I know exactly why they are there.

As illustrated in Matt's example above, the neuroscience information provided teachers strong rationales and understandings of brain functions to support good teaching practices. Similarly, Dana highlighted how the theoretical perspectives offered through neuroscience were essential in solidifying the lesson planning approach introduced through the LS – mainly, the use of event features and ensuring that the probes, pre-exposure, teaching and checks for understanding were aligned to the learning object and event features:

> (9) Dana (delayed post-lesson interview): It is important for people to be organized and to think about their teaching, to think about the way they are designing their unit. The neuroscience piece really solidifies it. It really gives it value and strengthens the argument for planning that way. *I think they go hand in hand. I can't imagine one without the other*. (emphasis ours)

In the same vein, Denise drew from the hRBT to explain gaps in students' understandings: event features are not well connected with existing neural networks, due to disconnection with students' prior learning experiences or students' lack of exposure to event features. Like several of the other teachers, Denise conceptualized her pedagogy as ways to help students connect otherwise disjointed even features and "set that [neural] network":

> (10) Denise (post-study interview): They have some sort of event features that is there, but it's not strong. So, it's there or it's not connected to other event features that we've looked at […] [or] connections that make sense to them based on their previous experiences, and maybe some haven't had that same exposure […] we have to work on building those connections […] I have to be conscious of the fact that we do have to go back and address that if I want them to move forward, to set that network, right?

Collectively, the excerpts above illustrated how the teachers incorporated scientific information about the brain into their existing frameworks for understanding, conceptualizing and articulating teaching and learning. However, it is worth noting that this took place with varying degrees of "success." For example, Ally mentioned in the post-study interview about how she still gravitated toward explaining her teaching practice using the VAK model, despite knowing it is a neuromyth.

Discussion

The study has limited generalizability due to its small sample size, with each team comprising of no more than five members. In spite of this limitation, the study was implemented over a longer period of time than most learning studies. This allowed for teachers from different grade levels to participate in the two LS cycles, where the increased diversity could enrich the data. This is also beneficial in view of how little is known about the application of neuroscience to formal teaching contexts.

The first LS team, comprising of teachers from different grade levels, deviated from typical configurations where teachers teaching the same grade work on a shared object of learning. Within the context of the school, it was not always possible to have group participants that were all teaching the same grade, which is likely to be a common logistical issue given staffing arrangements. Thus, the authors were open to having a "mixed" team configuration, where the upper and lower grade-level teachers worked on similar objects of learning within their sub-groups.

Overall, the findings suggest that LS is an effective teacher PD approach to support teachers' engagement with educational theories, beyond the dominant use of variation theory. This is in consonance with Runesson's (2016) study that explored the use of an alternative theoretical framework in LS. The current findings suggest that contemporary neuroscience information could support the goals of LS to support teachers' pedagogical practices and to increase student learning (Martin and Towers, 2016; Pang and Lo, 2012). Mirroring earlier learning studies (Holmqvist, 2011; Vikström, 2014), teachers in this study increased their sensitivity to students' learning through focusing on what and how students learn, as they developed sound, theory-framed pedagogy. This is evident in how teachers theorized and reflected on their instructional strategies in the LS setting (cf. Elliott, 2015), where they focused on students' mastery of the learning objects rather than on pedagogical acts. Crucially, teacher learning reported in this paper was not focused on specific instructional strategies *per se*. Rather, the teachers developed theoretical coherence in their understandings of teaching and learning, as is evidenced in all three themes presented.

Phrased differently, the impact of using neuroscience to frame the current LS may not necessarily lead to "revolutionary" or novel teaching methods. Nevertheless, much as is the case in "classical" LS designs where teachers use variation theory to support what many would consider good or "basic" teaching practices (cf. Tan, 2014a; Lo, 2012; Wood and Sithamparam, 2015), teachers here used theoretical neuroscience to support their pedagogy. Then, how neuroscience may reinforce seemingly "basic" teaching strategies is not surprising given that successful teaching actions are most likely to be those that are consistent with students' biology. Framed this way, the findings suggest that the teachers' participation in the LS promoted an evolutionary shift in their perspectives on human learning, resulting in their increased confidence about their selection of pedagogical techniques when introducing content. Much like variation theory, effective teachers have an intuitive sense of how to deliver content. Providing them with a sound theoretical frame allows them to hone their practice so that they can flexibly adapt their teaching in response to a wider variety of situations (cf. Elliott, 2015).

Unlike variation theory, neuroscience provided teachers with a theoretical lens for understanding biological underpinnings of human cognition, so that they could be more certain that their teaching was in line with students' biology. This is not to say that neuroscience is superior to variation theory. Rather, LS is an effective PD model where neuroscience could be employed to give another layer of depth to support teachers' praxis. In bridging the gap between neuroscience and teaching (Horvath and Donoghue, 2016), the study contributes to the debates around the potential application of neuroscience to classroom contexts (Bruer, 2016; Goswami, 2006). Importantly, this highlights the potential of LS to address the current controversies by providing educational practitioners with a context to test applications of theoretical neuroscience in classroom settings, with the goals of benefitting student learning and improving practice. This teaching–research nexus, made possible through LS, is consistent with Mayer's (2017) assertion that we should explore fruitful connections between neuroscience, psychology and education in order to advance the science of learning as well as the science of instruction.

In relation to teachers developing theoretical coherence in their teaching, the self-reported experiences presented here also challenge assumptions that teachers necessarily know about or are implementing their teaching practices with understanding. Quite on the contrary, the findings suggest that teachers require strong, compelling evidence to address questions of why they organize and teach their lessons in certain ways. LS literature has shown the value of providing teachers with learning perspectives and pedagogical tools (e.g. Pang and Lo, 2012; Wood and Sithamparam, 2015) to meet this need, although teachers' theory-guided pedagogical arrangements do not necessarily develop in tandem with their understandings of learning perspectives underpinning the theories (Tan, 2014a).

What is also iterated is the value of increasing the choice of pedagogical theories teachers could explore through LS, in order to widen their learning perspectives and repertoire of pedagogical tools, and to overcome challenges with using a single theoretical perspective (Lo, 2016). As a case in point, the centrality of event features to the participating teachers' lesson planning experience mirrors the pertinence of critical aspects to a learning object in variation theory (Lo, 2012). Both approaches help to focus teachers' attention on what and how students learn, albeit differences in what critical aspects and event features entail and the theoretical suppositions drawn upon; in short, variation theory is an extension of phenomenographic perspectives that are founded on psychological perspectives (see Marton and Booth, 1997), whereas neuroscience draws on biological mechanisms pertaining to human cognition and the brain. Nevertheless, it might be helpful to think of psychology and neuroscience as two sides of the same coin, with both fields adding to our understanding of learning in a way that advances the science of learning as well as the science of teaching.

Conclusion

The novel application of neuroscience perspectives can contribute to the development of LS by creating separation between the PD approach and its theoretical framework, and broadening the theoretical and practical understandings of teaching in relation to student learning. That is, collaborations between different professionals – such as teachers, neuroscientists and educationalists – with different theoretical understandings of learning contribute to increasing the breadth and depth of our understandings of teacher learning, student learning, the development of theory into practice-based applications and LS. In a mutually beneficial manner, employing neuroscience research findings as part of LS has the potential to bridge the gap that currently exists between neuroscience theory and educational practices. The result is that neuroscience knowledge becomes more accessible, examinable and relevant to teachers' existing practices. Although currently unexamined in the existing literature, at least to our knowledge, neuroscience-informed LS may be helpful to promote instructional strategies that form the foundations of good teaching practices that teachers may know of, but are not necessarily implementing. Of equal importance is how it could support teachers in developing understandings of the cognitive architecture underlying functions like learning and memory, allowing them to identify pedagogical actions that are consistent with human biology and understand why these actions are effective in promoting learning. For this purpose, it would be of interest to include other neuroscience research findings in future LS cycles. The study also supports the exploration of a diversity of theoretical perspectives that could further advance our understandings of teacher development in LS.

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