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On a New Taxonomy of Concepts and Conceptual Change: A Probabilistic Frame of Reference and Its Experimental Manifestations

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by

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I. Co-Authorship

I hereby declare that this thesis incorporates material that is result of joint research, as follows:

- *Chapters 3 of the thesis include the outcome of publication which have the following other co-author: Guoqiang (George) Zhou. In all cases only my primary contributions towards these publications are included in this thesis, and the contribution of co-author Guoqiang (George) Zhou was primarily through the following way: GZ contributed to the conceptualization, LL contributed to the review of literature and the manuscript preparation. GZ contributed to the discussion of the findings. The authors read and approved the final manuscript.*

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This thesis includes two original papers that have been previously published/submitted to journals for publication, as follows:

Thesis Chapter	Publication title/full citation	Publication status*
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ABSTRACT

This study focuses on the probabilistic aspect of international students' intuitive and counter-intuitive conceptions of pendulum motion. The probability here is rooted in a moving neural time average in the mind for characterizing students' cognition (sampling and decision making) and learning processes (resampling and making a new decision) rather than a frequentist's or a neural counter's way of keeping track of learning occurrences in the mind's conceptual space. I follow the daily use of the word "time" for any durable and differentiable interval that everyone can observe or measure directly and the words "reaction time" for any uncertain latency period in the mind/brain, an unobservable construct of the neural network timing theory. To sharpen the aforementioned focus, I argue that a new taxonomy of physics concepts is needed to save the mathematical identification of the classical and modern physics concepts, highlighting the role of such a renewed recognition of *the* language of physics brought to conceptual change studies. Over four decades of conceptual change studies have been based on the assumption that students come to the science classroom with their pre-instructional understanding of natural phenomena. However, it is largely ignored that the students' prior intuitive knowledge is probabilistic in time, representing some results of the idiosyncratic sampling of their daily experiences.

In this study, I built on such a conceptual linchpin to expand Zhou's (2012) hybrid space for science education to construct a two-dimensional time-based probabilistic conceptual learning theory. In particular, I asked the following research questions: 1) What are the roles of a mathematically defined physics concept (such as $T = 2\pi\sqrt{l/g}$) in influencing the sampling and decision-making processes during learning, which international students use to change their concepts in science learning? 2) How can the effects of such a Sampling and Decision-making mechanism be measured non-verbally? 3) What are the pedagogical implications of using the new taxonomy? To address these questions, I conducted two experiments to measure international students' conceptual change in time situated in the context of learning pendulum motion.

After reviewing pre-existing literature, I laid the foundation for a new theoretical framework of active learning with a probabilistic frame of reference. Next, a convergent parallel mixed-method research design was detailed to study the temporal aspects of students' active learning of pendulum motion. In Experiment 1, a pendulum period-matching was developed to prototype the experimental procedure for comparing the reaction times of making a correct or incorrect decision (a hit, a correct rejection, a miss, or a false positive) and to develop a new percentage correct analysis procedure. Experiment 2 examined international students' sampling and decision-making in a pendulum period-matching task of a string pendulum with cheeks. This experiment demonstrated the feedback's effect on changing the students' decision-making. Following the experiments, a qualitative study with five interviews showed students' false identification of irrelevant factors as the determining one and the fragmented nature of students' intuitive ideas. Together, the results have converged on the probabilistic aspect of students' active learning mechanisms in their minds. The manifold pedagogical implications of such a probabilistic cognitive "revolution" has also been discussed.

DEDICATION

In memory of his inspiring spirit of the beloved brother (Liu, Xuewei)

In recognition of the contribution and love of a supporting family: my parents, daughter, and wife

For my mothers' (Li, Qiyu and Li, Jinling) and fathers' (Li, Pizhi and Liu, Jianxi) witness of the completion of this research study journey

For Doreen Li, aged 10 and a Grade 4 student, who would argue, "*A thinking 'hat' is useless.*"

Along with my wife (Liu, Zhuohua), I hope I can convince her otherwise.

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The University of Windsor sits on the traditional territory of the Three Fires Confederacy of First Nations, comprised of *the Ojibwa, the Odawa, and the Potawatomi*.

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CHAPTER 1 INTRODUCTION

Imagine a jigsaw puzzle - a pile of variously shaped pieces spread on the table. In expectation, the curly and wiggly-edged cardboard fragments would fit together to form a complete visual representation of something familiar: a flower, a watch, or even a pendulum clock. Regardless of age, culture, or language background, the joy of seeing a complete picture of some sort emerging out of seemingly chaotic bits is a memorable experience which may have a lasting effect on one's problem-solving in future. However, occasionally, the joyful puzzle solver may come across a new piece shaped rather strangely. At first glance, it is a bit like part of a flower petal that produces nectar and attracts pollinators. However, after a careful re-examination, it also has the features of a pendulum bob.

Bearing these alternative classificatory possibilities in mind, the solver sees the edge of the unidentified puzzle piece as having information so bizarre that it cannot fit into the already-in-place boundary conditions of a half-way-completed picture of the flower or the clock. Even worse is such a scenario where she suddenly realizes there might be unknown missing ones waiting to be filled up. The revelation is alarming because solving the puzzle with previously unknown pieces signals that the current solution is not tenable, and the semi-completed "flower" may be something else. To proceed, she may have to think out of the "box" and reconceptualize what the whole jigsaw puzzle is really about: a flower, a pendulum clock or something else. When the unknown is assumed to represent a counterintuitive scientific concept to be learned, the characterization of playing such a hypothetical game is close to what initially caught the attention of a group of Cornell and Witwatersrand scholars forty years ago: conceptual change.

Both the opening example and conceptual change research focus on the unique uncertain aspect of working with a new concept or a conceptual system in problem-solving. Commonly, they assume a conceptual space for representing a problem's essential information, sampling thus-defined problem-solving sub-spaces, and deciding on possible solutions in time. For some researchers, the space is filled with emotional experiences or features of socio-cultural processes. I, in this study, assume a cognitive science perspective and take a closer look at how a new anchoring concept can be constructed, developed, upgraded, or even repurposed for solving a puzzling problem.

In science learning, such concerns are categorized under a thematic descriptor, conceptual change, a convenient umbrella term covering how learning communities and individuals update their knowledge. Ideally, when the conceptual change occurs, the group or the learner promptly considers available alternative solutions and immediately chooses to align with the theoretically sound and evidence-supported scientific perspective and its solution without going back to the initial uncertain status again, just like the old saying 不二错 (my translation: never commit the same error twice) in my mother tongue describes. Often this is not true. Meeting various students' mistakes or misconceptions is common in teaching and learning sciences. How to meaningfully address these intuitive pre-instructional ideas has piqued educational researchers' interest for forty years or more.

In the early 1980s, Posner, Strike, Hewson, and Gertzog (1982) published the article *Accommodation of a scientific conception: Toward a theory of conceptual change* in *Science Education*. Since then, thousands of theoretical and empirical studies have been documented in the literature using the same classifying term *conceptual change*, covering at least a narrow and broad sense of this classifier. Narrowly speaking, it refers to students' conceptual physics- or classical mechanisms-related learning phenomena. In this sense, the research focuses on transforming pre-college or college science students' misconceptions of some aspects of nature so that they can align with and appreciate a qualified theoretical or experimental physicist' view of the same phenomenon, such as the Brownian motion or the isochrony of pendulum motion. Broadly, the same classifier also refers to changing cultural, social, and philosophical attitudes or belief systems about science and science education systems over time, with a learner in such a social group changing her conceptions of a natural phenomenon laterally and concurrently. The subject matter of this dissertation is the first, narrower, and domain-specific sense of conceptual change.

A decade after Posner and his colleagues' original publication of the conceptual change study, calls for revision emerged in the literature. The reconsideration was made to address some identified flaws of earlier conceptual change research. For example, Strike and Posner (1992) themselves scrutinized and updated their initial theory in another publication *A revisionist theory of conceptual change* in an edited book *Philosophy of science, cognitive psychology, and educational theory and practice* (Duschl & Hamilton, 1992). They noted that "(p)erhaps what conceptual change theory requires is fewer teachers who emphasize calculating the right answer in their tests and instruction, and more teachers who emphasize the connections between physical conceptions, experimental evidence, and students' current conceptual ecology" (Strike & Posner, 1992, p. 171). Taking a similarly critical stance, Zhou (2012) urged researchers to reconsider the goal of twenty-first-century science education. He used a postcolonial framework to deconstruct the existing literature. He proposed a cultural approach to re-examine conceptual change research, especially when teaching culturally and linguistically diverse students in Canada.

Most importantly, he contended that today's science education occurs in a hybrid space, mixing the everyday, traditional, and scientific culture. The componential culture interacts with each other, creating "a unique and dynamic space" (p.118) for a science learner. In this sense, this conception of a hybrid science learning space for conceptual change is like the dynamic aspect of the student's conceptual ecology. These revisionist researchers have often urged educators to expand their theoretical horizons to reconceptualize the conceptual change challenge.

Although the calls have been expressed loud and clear, most have been mainly ignored. This study aims to answer them by foregrounding a previously unattended aspect of the existing research: the science of uncertainty and conceptual change. In particular, I foreground the concept of probability and a sampling and decision-making mechanism (the S-D mechanism thereafter) so that I can take a closer look at the finer details of conceptual change processes, especially from a different temporal perspective. Putting on the sub-second temporal lens or a non-verbal prism, I could see the same conceptual change process from a new perspective. By highlighting the non-deterministic nature of concepts and conceptual change, I join the force with cognitive scientists to adopt the strategies of using psychologically plausible mechanisms for understanding conceptual change. To construct such a psychologically real conceptual-change-in-time theory, I ask: What would a new taxonomy of concepts and conceptual change look like if human information processing is probabilistic? With the aid of a paradigmatic example that connects the mathematical idea of a simple harmonic oscillator, pendulum physics knowledge, and learning pendulum motion, this dissertation also addresses the following physics education research (PER) related questions:

1. What are the roles of a mathematically defined physics concept (such as $T = 2\pi\sqrt{l/g}$) in influencing the sampling and decision-making processes in human reaction time during learning by which international students use to change their concepts in science learning?
2. How can the effects of such a S-D mechanism be measured non-verbally?
3. What are the pedagogical implications of using the new taxonomy?

Sciences, the Science, and Science Education

To avoid unnecessary confusion, I begin with a keyword analysis, with a focus on the phrase “conceptual change in science learning” and its constitutive parts, such as the word “concept” and “science.” In particular, I distinguish the singular-versus-plural word form of the English word “science” because the thematic classifier conceptual change is often defined in the context of science education. Without a proper understanding of such a distinction, it is hard to identify and explain the intended change process satisfactorily. Also, I make another general-versus-specific analysis of the English word “concept” because it helps English as a Second Language (ESL) readers understand the meaning of the term.

According to Oxford English Dictionary (Oxford University Press, 2023), the English word "science" is a borrowing from French *science* and connects with the Latin word "*scientia,"* which means knowledge as opposed to belief. Today, both French and English words “come to be the usual term for those branches of study that deal with a connected body of demonstrated truths or observed facts systematically classified and more or less comprehended by general laws, the French word continues to have rather broader application than the English word to knowledge as acquired by study, experience, or reflection” (ibid). In accordance with *Stanford Encyclopedia of Philosophy* the English word "scientist" was first coined by the English polymath William Whewell (1794 - 1866), responding to the poet S.T. Coleridge's challenge in 1833. Before the invention of this word, the only terms in English were "natural philosopher" and "man of science." In modern use, the word "scientist" refers to a wide range of professionals who engage in scientific research activities in various disciplines, such as physics, chemistry, biology, and other subjects.

Both the words *science* and *scientist* are taught early in Canadian schools. However, the meanings associated with their plural or singular forms are not fixed, with their meanings determined by the contexts in which they are used. As a collective naming word, the symbol can be interpreted as referring to the domain of general knowledge. In this sense, the root form symbol *science* collectively refers to teaching and learning Physics, Chemistry, Biology, or Geosciences, with its derivative *sciences* covering more similar subjects. Such a domain-general interpretation of science informs the subject matter-general approach to science education, which features basic-level terms and general investigative procedures in sciences.

Adopting such an approach is reasonable because the boundary separating each science discipline has not been established yet in those earlier years of primary schools. Science students are still in the stage of learning their first languages and basic level knowledge. However, this is going to change. Some form of specialization is needed beyond the K-8 science education. The label "science" can be modified with an English article "the" to capture this extra layer of sense, thus forming the science, which refers to Grade 12 Physics or Chemistry as an independent subject. Take the subject of Physics for an example. The science here means a unique knowledge matrix covering classic Mechanics, Relativity Theories, Quantum Mechanics, etc. Here, the conceptual change approach is still "a powerful framework" (Duit & Treagust, 2003) to tackle the challenge of science education. For college students, regardless of whether they majored in science or not, the word science means more than a combination of known theoretical concepts and demonstrated experimental results. They may have to learn how to construct their conceptual bases to respond to anomalous data (Chinn & Brewer, 1993) or use anchor equations (Redish, 2021) to solve problems meaningfully. These conceptual change learning concerns are mainly addressed in the research field: Physics Education Research (PER).

Concept, Conception, and Conceptual Space

In the study of student conceptions in sciences, the English words “concept” and “conception” are also needed to be differentiated. According to *Oxford English Dictionary* (Oxford University Press, 2023), a concept refers to something conceived in mind: a notion, a general idea, or a cognitive representation of a phenomenon, whereas conception could have two meanings: (a) bearing a child, (b) perceiving something in mind or the psychological process of forming and comprehending a concept. For the purpose of science education, a physics concept or a system of theoretical concepts are all learned cognitive representations or mental models constructed in a learner’s mind. For an individual learner, her conceptions can vary dramatically, ranging from a misguided misconception to an evidence-supported and scientific community-endorsed one.

In Thomas Kuhn’s (1970) late works on concepts, the science historian stressed a distinction separating the normic from the nomic. According to him, normic concepts are learned cognitive reconstructions with observable family resemblance, with some easily detected similar and dissimilar features to define each family, such as the rod length or the pendulum string's colour. In contrast, nomic concepts are acquired in a theoretical language; their family resemblance is to the mind’s “eye” (Sacks, 2010), which can only be found in problem situations, such as explaining the oscillation period of a simple pendulum, or through mathematical routes such as using a complex number, a matrix, or an irrational number π. In studying students' conceptual change in science learning, how to conceptualize a physics problem in a theoretically meaningful way is a crucial factor. In this study, I adapt Gärdenfors' conceptual space (2000) for further developing Zhou's (2012) hybrid learning space. According to Gärdenfors and Zenker (2010), conceptual spaces are represented as dimensional spaces in mind, with information idealized either as points in such a space (acting as a substitute for individuals or objects) or surface areas (standing for relationships or properties) in it. Within a conceptual space, the distance between the points corresponds to the degree of similarity among objects. In their own words,

> A conceptual space consists of a number of quality dimensions. Psychological examples of such dimensions connected to sensory impression are color, pitch, temperature, weight, and the three ordinary spatial dimensions. However, in scientific theories the dimensions are determined by the variables presumed by the theory. We have already noted that within NPM (Newtonian Particle Mechanics, added explanation) the relevant dimensions are three dimensions of space, time, mass and three dimensions of force. (Gärdenfors and Zenker, 2010, p. 141)

My probabilistic adaption of the conceptual space toward a new hybrid learning space will be detailed in Chapter 4 after two literature review chapters.

A Taxonomy of Science Concepts for Advancing Conceptual Change Research

After clarifying science and concept, another aspect of characterizing scientific knowledge is its organization. In this aspect, the term *taxonomy* occupies a unique position in a learner's conceptual space. To most of us, a taxonomy in biology refers to a hierarchical and embedded categorical system for identifying and classifying organisms given their physical and genetic characteristics. With such a categorization, a biologist can categorize the diversity of living organisms into an ordered and accepted theoretical system (Species, Genus, Family, Order, Class, Phylum, Kingdom, Domain) into various sub-conceptual spaces. These sub-spaces embody a set of premises and organizing principles so that the stability and consistency of these categories and inter- and intra-relationships among living organisms can be represented, with the points representing animals or plants and the areas representing their connections. One of the primary goals of modern science education is to help students understand the taxonomy so that they observe an ecological environment with their mind's eyes and are ready to solve new problems even if seeing abnormal data or surprising experimental results. The benefits of using taxonomy in research are also familiar to non-biologists.

One widely known example is Bloom's *Taxonomy of Educational Objectives* (1956). After half a century, one of Bloom's students, Lori Anderson and David Krathwohl, who were joined by a group of educational psychologists and educators, published a revised version of Bloom's taxonomy in 2001. In contrast to the biologist's and educators' taxonomies, another famous classification system is the *Diagnostic and statistical manual of mental disorders: DSM-5-TR* (First & American Psychiatric Association, 2022), highlighting its probabilistic nature in categorizing mental health-related conditions. Inspired by such an effort and the idea of cognition-as-intuitive-statistics (Gigerenzer & Murray, 1987), I would ask: What about the concepts and conceptual change if a learner's cognition or conceptual space is assumed to be running on an intuitive statistics-based mechanism?

The Outline

The purpose of this study was manifold: (a) to break away from a utilitarian tendency in science learning and teaching studies while emphasizing the importance of probabilistic thinking and the moving neural time average in a hybrid conceptual space, (b) to highlight the limitation of using any single natural language without considering time for describing the physics concept change process, (c) to substantiate the benefits of employing a new 2-dimensional construct of time for such measurement, and (d) to incorporate the moving time average-based cross-cultural and bilingual element in conceptual change studies. Most importantly, reconsidering conceptual change as reweighting personal knowledge distributions affords new opportunities to generate falsifiable predictions regarding conceptual change experiments for science learning. In the next chapter, I will review the qualitative conceptual change studies, followed by a separate chapter on conceptual change measured in time. An active S-D theoretical framework and methodological considerations are detailed in Chapters 4 and 5. Following the methodology chapter, two experiments are reported in Chapters 6 and 7. These quantitative studies were complemented by five post-experiment interviews documented in Chapter 8. Discussions and implications of these results are elaborated on in the last chapter.

CHAPTER 2 CONCEPTUAL CHANGE STUDIES: A FORTY-YEAR RETROSPECTIVE

More than 40 years of research efforts, starting with a study on conceptual ecology, have spawned thousands of qualitative and quantitative studies bearing the same keyword: conceptual change (Duit, 2009; Duit & Treagust, 2003). However, these research endeavours are unevenly distributed, over-relying on qualitative research methods and verbally reported data. The disparity is so pronounced that the distribution of previous research efforts even renders a body of experimental results of conceptual change seemingly unapproachable. This may not be a problem for those researchers who have chosen to focus only on philosophical reflection, verbal expression, and nominal data. However, the practice has, in effect, isolated them from fundamental cognitive mechanisms of learning in the brain and the voices of mathematicians, experimentalists and physics education researchers (PER) in science education. For a PER researcher in particular, the ignored aspects of current conceptual change studies are what is needed, especially when viewing from the half-verbal-and-half-mathematics perspective of a physics concept. In this sense, learning a new concept means more than acquiring a new English word or phrase. To provide an all-encompassing view of conceptual learning in PER, I have divided the literature review into two parts: qualitative and quantitative sections. This chapter focuses on the qualitative research thread of conceptual change studies.

For thousands of qualitative studies, a representative voices sampling strategy is adopted to summarize this body of literature, with no attempt to achieve an inventory-like comprehensive review of qualitative results. For interested readers, Reinders Duit (2009) published a Students' and Teachers' Conceptions and Science Education (STCSE) bibliography, with its latest version covering 6952 entries. More recently, Potvin et al. (2020)

also published an inventory-like summary of conceptual change models in science education. To reveal the conceptual gap in current literature and the need for a new taxonomy of concepts and conceptual change for domain-specific conceptual change studies, I start by addressing what conceptual change is and is not.

What is and is not Conceptual Change?

In terms of understanding a counterintuitive scientific idea, conceptual change can be first seen as an ideal learning process or a "knowledge restructuring" process (Schneider et al., 2012), which features a typical sequence of active information processing. In their words,

> The structure and content of a learners' prior knowledge determines how new information is interpreted and stored in memory. New concepts that are not fully compatible with prior knowledge can, thus, only be learned when the network of prior knowledge is restructured. (p. 736)

Earlier, Davis (2001) illustrated the same process using a ninth-grade student's story, in which she had to figure out the mechanisms behind the four seasons of a year and the phases of the moon. In his formulation, the learning process "is generally defined as learning that changes an existing conception (i.e., belief, idea, or way of thinking)" (p.184). Similarly, Zhou et al. (2008) observed "(p)reconceptions serve as a platform from which students interpret their world. Unfortunately, in most cases, preconceptions are quite different from scientific notions. Learning under these circumstances involves the restructuring of preconceptions" (p. 15). Commonly in these formulations of conceptual change, the term *concept* refers to more than those isolated pieces of knowledge. In effect, it refers to a (sub)system of a sense-making network with various branches and deep connections. The same can also be said about the term *change*, and it has caused more controversies than agreements.

In the literature, conceptual change has also been referred to as knowledge "tree switching" (Thagard, 1990), reintegrating "Knowledge in Pieces" (diSessa, 1993), re-assigning ontological categories (Chi et al., 1994), restructuring a theoretical framework (Vosniadou, 1994), or a kind of "coexistence between scientific understanding and culture/experience-based views" (Zhou, 2012). Given these opinions, it is evident that science educators have not reached a consensus on what conceptual change is. Having described what conceptual change might be, it would also be informative to ask the opposite: what it might not be.

Influenced by the philosophy and history of science, Strike and Posner (1982) differentiated a small-scale conceptual change from a large one. According to them, only the latter is "analogous to Kuhnian 'paradigm changes' or Lakatosian 'shifts between research programmes'" (p. 233), which would qualify for a proper conceptual change. In contrast, the small-scale assimilation of knowledge fragments is not. The borrowed distinction between conceptual assimilation and accommodation implies the possibility of replacing one central concept with a to-be-learned one through "the kinds of radical conceptual changes" (Posner et al., 1982, p. 213). However, this is not the only way to tell their differences.

To Chi (2008), learning science concepts can occur under at least three conditions of students' pre-instructional ideas. For example, she may know nothing about the to-be-learned concepts. In this case, adding new knowledge would be sufficient for learning. At other times, she may have partial knowledge about what is to be taught in her school. Therefore, she would engage in the gap-filling type of learning. These cases are not the "conceptual change kind of learning" (p. 61). Alternatively, she may acquire concepts somewhere else which are in direct contrast to the to-be-learned ones. Only under this condition the proper conceptual change process can be assumed. In brief, both Strike and Posner (1982) and Chi (2008) have viewed students' learning difficulties as an incompatible pre-instructional conceptual system, which ought to be replaced with understanding new science conceptions. Thus, other types of learning are not conceptual changes.

Similarly, diSessa and Sherin (1998) asked, "What changes in conceptual change?" (p.1155). They proposed a knowledge system approach to conceptual change. From their perspective, the concept is identified as coordination class. Therefore, conceptual change involves integrating diSessa's (1993) phenomenological fragments in a learner's mind (P-prims for short) to read out invariance across situations. For them, knowledge acquisition without P-prims reintegration is not conceptual change. In brief, not all learning can be qualified as a conceptual change in science education, especially when considering the initial triggering theoretical consideration of conceptual change research. To develop a new taxonomy of concepts and conceptual change for PER, I seek a new definition of a concept that fits the reality of science students' working memory structure for this study.

In PER, the scientific concepts students learn about, like forces, energy, and the oscillation period of a simple pendulum, are based on a combination of empirical laws, mathematical equations, and experimental data, which are activated in their minds to explain how things work in nature. Given such consideration, it is necessary to foreground such a connection and differentiate a physics concept from other ones. To this end, I first define a concept as a half-verbal-conception-and-half-mathematics structure. For example, the definition of pendulum period $T = 2\pi \sqrt{l/g}$ is a perfect case of this type of concept. In this concept, there are mathematical constants or approximate ones, such as 2, π, and g, if only considering one fixed observation location on the earth's surface. Moreover, the mathematical relationship in this equation can be characterized as a scaler product featuring a multiplying connection between the constants and variables. Furthermore, there is a co-varying relationship connecting two variables to the left and right sides of the equal sign. At last, the often-ignored aspect of this empirical equation is its nature as an approximation to a simple harmonic oscillator swinging within a small release angle of the pendulum. Out of such a boundary condition, the predictive power of such a mathematical construct is lessened; thus, a new full-term version of pendulum motion is needed. In this sense, this classical model of a deterministic system can also be seen as becoming probabilistic. In brief, physics concepts or concepts in PER differ from the psychologists' concepts defined over sensory or perceptual similarity. However, their activation and processing mechanisms in a learner's brain may be similar due to a common cognitive system, which may or may not have common temporal trajectories. Before detailing the connection between the new taxonomy and conceptual change studies, I first review the qualitative aspect of the research field.

Setting the Stage: The Problem of Conceptual Change in Philosophy of Science

Given that the early stage of solving the conceptual change problem (Posner et al., 1982; Posner, 1982; Strike & Posner, 1982) was heavily influenced by the viewpoints originated from the philosophy and history of science (Kuhn, 1970), the problem situation viewed by science philosophers and historians was first revisited. It should be noted that the elements of experimentalism can be found in the philosophers' discussions of conceptual change, but it had never occupied a center stage in solving the problem. Instead, a justified belief system, propositions, or theoretical and observational statements were the keywords in their discussions. In essence, the science philosophers' conceptual change problem stemmed from an influential historicist's critique of the logical positivists' ideal of unified science (Kuhn, 1970).

> The (logical positivist) idea was that any concept, from any branch of science (physics, chemistry, biology, astrology and the others), had to be "statable by step-wise reduction to other concepts, down to the concepts of the lowest level which refer directly to the given" (Hahn et al., 1996, p. 331). On this lowest level there were supposed to lie concepts of "the experience and qualities of the individual psyche"; on the next, physical objects; then, other minds; and, lastly, the objects of social science (Hahn et al., 1996). The method logical positivists used to move in and deal with this hierarchical system of concepts was logical analysis, undertaken with the help of the formal logic developed by Frege and Russell at the start of the 20th century. (Arabatzis and Kindi, 2013, p. 343)

To the logical positivist Carnap and those in the Vienna Circle, conceptual change was merely a problem because their formal logical analysis was thin in content and rich in symbolic rules. According to them, they set to differentiate two types of statements (the explanans and the explanandum) for understanding scientists' explanations of an observation. An explanans is a statement that expresses general scientific laws, and the explanandum describes a specific observation to be explained. They were more interested in studying the interconnections between observational and theoretical statements, not the contents or the structure of concepts embedded in them. To them, clarifying a theoretical concept meant connecting the theoretical statement back to its basic set of sensory experiences. Equipped with such a conviction, scientific concepts as objective terms were there to avoid the subjective aspects of a concept. Accordingly, a conceptual change in a learner's mind as a problem was minimized and reduced to a measurement-related one.

In other words, logical positivists or logical empiricists were more interested in revealing the formal structural aspects of the relations between statements rather than the real contents of a concept. In this sense, they were looking for an ideal formal system, “an axiomatic, hypothetico-deductive, empirically uninterpreted calculus which was then interpreted observationally by means of bridge principles or correspondence rules” (Arabatzis & Kindi, 2013, p. 344). For them, conceptual change as a problem was not as interesting as that of manipulating concepts or terms rigorously and mechanically according to a predicate calculus among statements.

In responding to the logical positivist’s unifying science ideal, the science historian Kuhn, in his *The Structure of Scientific Revolutions* (1970), argued that a scientific concept such as that of the ether, the absolute space, or pendulum motion was just an ephemeral and historical time-based intellectual product that evolved with theories in time and over paradigms. For a specific period of historical time and within a particular paradigm, a concept that only bore a fuzzy Wittgenstein’s family resemblance with other concepts exerted its influence in normalizing and stabilizing scientists’ activities. Over paradigms, the intellectual product can be radically transmuted, transformed, and replaced by a newly developed one. For example, the quantum field theory replaced the once-foundation-stone-like concept of ether. Similarly, Albert Einstein’s spacetime was to renovate the notion of Newton’s absolute space. According to the historicist view, the discussions of a preceding concept and its subsequent one over paradigms were sometimes unrealistic because they might, in effect, refer to totally different things in the world. Thus, the subject matter of scientists’ research efforts can not be compared after such a radical conceptual change, making a unified science ideal problematic.

Moreover, the Kuhn era's philosophers maintained that scientists' observations were theory-laden (Hanson, 1965), making the distinction between observational and theoretical statements untenable. Once the grip of a unifying science being loosen, Kuhn and those like-minded philosophers highlighted the role of science education in forming and reshaping young students' knowledge structure and conceptual change by exposing them to concrete problem situations, exemplary solutions, a shared consensus, and a commitment in how to use a scientific concept (Kuhn, 1970). These tradition-defined or science textbook-shaped learning and research activities were Kuhn's normal science. When practising in this way, the scientists were a group of research tradition defenders or fundamentalists.

However, that is only part of the story. The same scientists were also reformers when anomalies in normal scientific activities (such as the ether can not be experimentally verified) had become obvious. However, "(n)ovelty ordinarily emerges only for the man who, *knowing with precision* what he should expect, is able to recognize that something has gone wrong" (Kuhn, 1970, p. 65; originally emphasized). Suppose the apparent anomalies kept showing up to become unavoidable obstacles. In that case, they must reconsider their beliefs and normal practices to rebuild the field so that novel theories and new experimental paradigms can be integrated into a new whole. As a result of such a radical conceptual change, those "once-abnormal" theoretical considerations and experimental practices were gradually established as the new normal science.

> So, scientific practice is a dynamic, developmental process punctuated occasionally by radical changes which produce theories that are incommensurable with the previous ones. This means that the new theories cannot be mapped onto the old, new relations are established between concepts and laws, and new exemplars occupy the knots in the new

> framework. The two systems, old and new, lack a common core or a common measure. Concepts in the new context, even when they continue to be named by the terms used in the previous theories, or even when there is quantitative agreement in calculations that involve them, still are viewed by Kuhn to be markedly different. (Arabatzis and Kindi, 2013, p. 348)

In such a historicist view, conceptual change was a critical transformative factor to enable Kuhn’s scientific revolutions in the history of the Western sciences, thus achieving advancement in science. The price that such a revolutionary change had to pay was that it might not be easy to map out the intertheoretical connections between the two sets of incompatible concepts of the replaced theory and the replacing one.

> Or take Kuhn’s example: if an Aristotelian saw a constrained stone swinging on a string, he would not have seen a pendulum. No such pendulum category existed at that time, though the concepts of equal time and equal spaces did. (Machamer, 2007, p. 42)

In addition to these influences in history, another source of conceptual change inspiration comes from Jean Piaget, a Swiss psychologist (Müller et al., 2009; Siegler et al., 1973). According to him, children pass through distinct stages of cognitive development, each with unique ways of perceiving their living environments, thinking, and problem-solving. To understand these children's cognitive processes and their developmental stages, Piaget developed the clinical interview method. This method involves asking open-ended questions to a child to get a sense of their thought processes and cognitive abilities. The method also inspires educators to implement it to understand how children think, learn, and develop their cognitive abilities at each stage of development. Nevertheless, Kuhn’s ideas of paradigm change and incommensurability, along with Piaget’s clinical (critical) interview method (Posner et al., 1982; Müller et al., 2009; Zhou, 2010), were borrowed by science educators in the 1970s (Posner et al., 1982; Posner, 1982; Strike & Posner, 1982) to tackle their students' learning problems, such as learning Albert Einstein's relativity theories.

Cornell and Witwatersrand Scholars' (1982) Initial Theoretical Consideration

Back in the late 1970s, coming with an academic conference celebrating a ground-breaking scientific theory was an initial expression of conceptual change concern. With a conference paper *Learning Special Relativity: A Study of Intellectual Problems Faced by College Students*, a group of Cornell education scholars presented a paper at the International Conference Celebrating the 100th Anniversary of Albert Einstein on November 1979 at Hofstra University, USA. Later, this conference paper was published as a seminal journal article bearing the name "A theory of conceptual change". In this article, the student's learning difficulties were seen as coming from understanding a physics concept: Spacetime, a brainchild of the physicist Albert Einstein (1879-1955) and his mathematics instructor Hermann Minkowski (1864-1909). Mathematically, the big idea relies on a unique and bizarre notion: the square root of minus one: *i*. Only by expanding a real three-dimensional space to include this unusual imaginary number as a unit could it be possible to construct a space-mergeable dimension (*i*ct) or the physicist's time (Canales, 2015). The idea can also be explained in a non-Euclidean geometry involving Hermann Minkowski's four-dimensional construct. Although counterintuitive, the notion of Spacetime helps construct a block view of the universe and the world line of an event embedded in it. Thus, the notion has become essential in articulating and understanding the big ideas in modern physics.

However, learning such a big idea is challenging because similar physics concepts to novices are remote, abstract mental constructs backed up by mathematics, such as Hilbert space, complex analysis, and the mathematical group theory (Longair, 2020). Commonly, these half-and-half conceptions violate most learners' intuitive ideas of two separate dimensions, space and time. Thus, teaching and learning such a conception was like learning to swim against the natural direction of mental torrents. Indeed, the life story of conceptual change theories was stamped with a struggle to promote students' understanding of those mathematical physics-supported conceptions.

Posner, Strike, Hewson, and Gertzog (1982) proposed a cognitive ecology theory to address the conceptual change challenge. According to them, a total of an individual's current concepts, her conceptual ecology, are the key determiners of the direction of accommodating a physics concept such as spacetime. The conceptual ecology covers at least five types of cognitive and metacognitive constructs, such as "anomalies, analogies and metaphors, epistemological commitments, metaphysical beliefs and concepts, and other knowledge" (pp. 214 - 215). Although these researchers did not characterize the conceptual ecology as a non-deterministic system, it evidently features a probabilistic characteristic considering their interaction among these components. Suppose such a probabilistic cognitive ecology interpretation is reasonable. In that case, the change process is highly likely to follow the same characterization, especially when activating these concepts in human memories is a probabilistic procedure.

Guided by the cognitive ecological view, Posner et al. (1982) championed the replacement view of conceptual change. They contended that students are like pre-paradigm-change researchers in the past, with intuitive but "incorrect" ideas about the world. These pre-instructional misconceptions are deeply implanted in their cognitive structures, influencing subsequent science learning in an unwanted manner, such as interfering with instructors' teaching efforts. They resist changes because they grow out of students' own living experiences outside science classrooms. More effective science teaching and learning can be expected only after replacing interfering misconceptions.

Given such a misconception-based view of students' learning difficulties, they differentiated two types of modifications upon these misconceptions: assimilation or accommodation. They describe how students incorporate new information into their existing cognitive structures (assimilation) and adapt their existing structures to accommodate new information (accommodation). Through the former process, science students slightly modify the established knowledge structure to absorb the new information, fitting new experiences or knowledge into our pre-existing mental structures without fundamentally changing them and thus not conceptual change per se. In contrast, by the accommodation process, a learner reconstructs her previously held knowledge structure, thus enabling the learner to see a natural phenomenon in a new way and explain it like a post-paradigm-change expert. That is to say, when new information contradicts or challenges the students' existing beliefs or knowledge, they need to accommodate by adjusting our mental frameworks to better align with the new information. In this sense, a conceptual change can be claimed to have occurred and improved the subsequent learning processes.

Foregrounding the accommodation view of conceptual change shows burgeoning research activities in teaching and learning the fundamental science, which has remained active since the 1970s (National Research Council (US) Committee on Undergraduate Physics Education, 2013). That is to say, conceptual change study in those early days was most active in a few subject areas, such as physical science, because the knowledge of physics is so close to student life and their misconceptions are most saliently related to the fundamental science. For example, the illustrative case study in the seminal journal article was about learning Albert Einstein’s Special Theory of Relativity. In their own statements, Posner et al. (1982) expressed their concerns over students’ understanding of "the workings of a light clock and the implications it has for the concept of time" (p.215). Likewise, Hewson (1982) singled out the notion of time dilation in his case study to show prior knowledge's effect on science learning. These conceptual ecological theorists were motivated by the challenge of teaching modern physics theories, which inevitably involves a new concept half-and-half-defined.

Similarly, Gunstone (1994) argued that demonstrations that yield unexpected results (discrepant events) can be employed to draw students' attention and challenge their conceptions of a phenomenon. In his view, these dissonant occurrences were effective in science teaching because they helped create a puzzling situation that tended to lead to cognitive disequilibrium. The cognitive instable status would in turn prime the need for students to assimilate (use existing knowledge to deal with new experiences) or accommodate (alter or replace existing conceptions) their pre-instructional conceptions to make senses out of the unexpected and puzzling outcomes. Unfortunately, the birthmark of this opening conceptual change study cannot be easily seen today. However, that does not mean the teaching and learning challenge also disappears. On the contrary, its urgency has become more salient. In this sense, conceptual change researchers face the same challenge as those earlier theorists did in history. One shortcoming of earlier conceptual change studies is avoiding the nature of physics concepts and mathematical reasoning to suit education research paradigms. Whether or not this was a wise decision is another issue.

One of the identifiable features of such a misconception-based view of conceptual change is the assumption that alternative student conceptions are a system-like cognitive structure deeply rooted in the mind as a cognitive ecology. Four conditions must be met to change or upgrade such a pre-instructional knowledge operating system: (a) a dissatisfaction with existing conceptions must be induced, (b) a new conception must be clear or intelligible to students, (c) the new one must be capable of addressing the dissatisfaction or initially plausible, and (d) it should have a potential of solving more similar problems. According to Duit and Treagust (2003), this pedagogical model "was refined by Hewson (1981, 1982, 1985, 1996), Hewson and Hewson (1984, 1988, 1992), Strike and Posner (1985, 1992) and applied to classroom instruction by Hennessey (1993)" (p. 673). Commonly, this line of conceptual change studies has assumed a coherent student cognitive ecology in affecting the direction of conceptual change. However, another theoretical view would soon challenge this systematic misconception assumption: the knowledge-in-pieces.

The Rise of Conceptual Change Research

After the publication of Posner and his colleagues' seminal paper, the growth of conceptual change studies became apparent, with several lines of development pursued by different groups of researchers or individual researchers, such as Andrea diSessa, Alison Gopnik, Paul Thagard, Michelene Chi, Stinner Arthur, and George Zhou. For the purpose of this dissertation, the scope of a qualitative literature review is established toward Canadian scholars' works, especially those living in the province of Ontario. In addition, the review concentrates on adults' learning rather than K-12 education because the latter's language system is still under development, and their formal mathematical knowledge is not stable, especially for children. Besides these two considerations, the review also focuses on the subject areas within the boundary of physical sciences. The reason is the domain-specificity origin of this line of research, as reviewed in Section 2.2. In brief, to develop a new taxonomy of concepts, I have tried to focus on the physical sciences-related conceptual change literature contributed by Canadian scholars studying post-secondary science education and point out the reference links for the developmental and sociopolitical studies of conceptual change studies.

Rather than seeing students' conceptions as a cognitive ecology, diSessa (1993) asserted that there are much smaller sense-making units (Phenomenological primitives or P-prims for short, in his own words) acting as assembling pieces for constructing students' intuition about the world. The fragmentary phrase "force as a mover" is such an example of P-prime. Other P-prims include resistance and dying away/warming up for studying students' learning of the classical mechanism in physics. These units are supposed to help students develop a physical sense of mechanism. In his own words, "(i)n dealing with the physical world, humans gradually acquire an elaborate *sense of mechanism* - a sense of how things work, what sorts of events are necessary, likely, possible, or impossible" (p. 106). From these conceptions, he continued to claim the structure of this sense of mechanism as a knowledge system.

Starting with such a knowledge system, diSessa (1993) asked a series of questions, such as what the elements of the system are and to what extent they are isolable. In his monograph *Toward an Epistemology of Physics*, he questioned the validity and applicability of the cognitive ecology view of replacing students' misconceptions. Instead, he advocated treating students' preconceptions as an inconsistent and fragmentary knowledge base, which can be further developed to change into scientific physics conceptual systems. From such a perspective, the fragmented P-primes would be dynamically activated in the learning mind to respond to a specific problem situation in an emergent manner. In this sense, deeply rooted misconceptions can not be viewed as a cognitive ecology but as assembling activated fragmentary knowledge pieces (such as an incomplete and partial equation, the intuition of force-means-movement) in the working memory. For the latter, who endorses the P-prim theory, a physics concept is identified as Coordination Class. Hence, conceptual change means integrating P-prims to read out invariance across physics problem situations. For a P-prim theorist, the learning process without P-prims uptake and reintegration is not conceptual change per se.

Against the structure-less or fussy P-prim-based view of conceptual change, Chi and Slotta (1993) proposed an ontological category shift theory of conceptual change. According to this ontological mis-categorizing view, students' learning difficulties are not originated from the cognitive ecology or reusing P-prims but rather the misplaced organizing concepts. Here, grouping heat as a thing-like object rather than a movement-based process is an example of this type showing the mismatch between students' intuitive ideas and the established scientific view. To Chi (2008), learning physics concepts can occur under three conditions of students' pre-instructional conceptions. First, they may know nothing about the to-be-learned concepts. In this case, adding new knowledge would be sufficient for learning. Second, they may have partial knowledge about what to be taught in their school. Hence, in this case, she would engage in the gap-filling type of learning. These cases are not the "conceptual change type of learning" (p. 61). At last, they may acquire concepts somewhere else which are in direct contrast to the to-be-learned ones. Only under this condition, the proper conceptual change process would get involved to shift students' misplaced organizing concepts to get the scientist's view. In brief, both Strike and Posner (1982) and Chi (2008) have viewed students' learning difficulties as originating from incompatible pre-instructional conceptual systems' influences on processing the to-be-learnt information; thus, they ought to be replaced or re-categorized to get the scientist's view.

Also in the 1990s, when the now-Canadian scholar Paul Thagard worked in the United States, he published a synthesis *Concepts and Conceptual Change* (1990). In contrast to Posner and his colleagues' cognitive ecology and Chi's ontological misplacement and shift, he championed the idea of ranking the degrees of change. In his words,

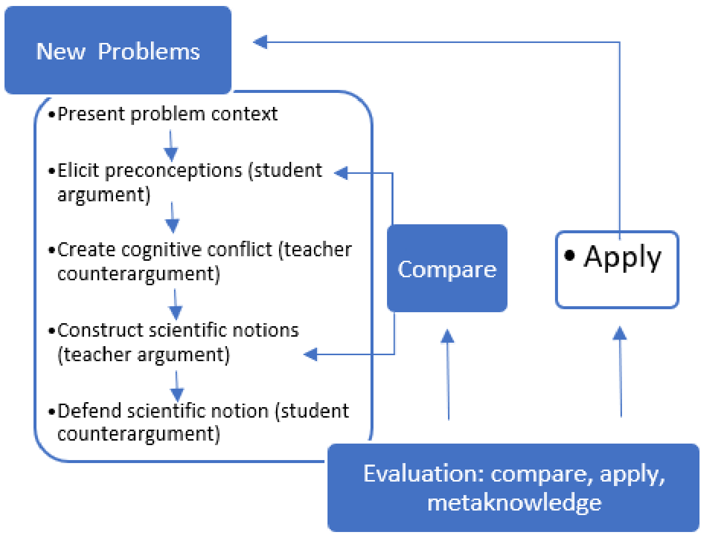
> It would be futile to try to offer criteria for identity of concepts that attempt to specify when a concept ceases to be the concept it was. We cannot even give such Criteria for mundane objects like bicycles: if I change the tires on my bicycle, is it the 'same' bike? What if I change the wheels, or the frame, or all of the above? But without giving a definition of sameness for bicycles, we can nevertheless rank degrees of change. Replacement of the parts mentioned are all changes in my bicycle, but it seems clear that changing the frame is a more severe change than the wheels, which is more severe than changing the tires. Similarly, we can characterize different kinds of conceptual change and see that some are more serious than others. (p. 267)

In this degree-of-change sense, the replacement or categorical shift suggestions would be problematic. Instead, he constructed a list to show the severity of conceptual change. I relist his catalogue from the most severe to the least. They are (a) (conceptual) Tree switching (in the working memory), (b) Branch jumping to reorganizing hierarchies, (c) Adding a new concept, (d) Adding a new relationship, (e) Adding new part-whole relation, (f) Adding a new strong rule, (g) Adding a new weak rule, and (h) Adding a new instance. With his degree of change theory and in the heyday of connectionism and neuroscience in psychological science, he paved the way for the parallel distributed processing-like computational approach to tackle the conceptual change problem.

In terms of applying concept change theories to the science classroom, another Canadian Scholar, George Zhou, outlined an argumentation approach to the conceptual change problem (2010). The unique aspect of such an approach is its combination of student and teacher argument components within a single framework (see the reconstructed Figure 1 for detail). The reconstructed illustration shows there are two rounds of argument-versus-counterargument embedded within the stage of presenting a problem context and evaluation. In the middle of the process, student preconceptions are to be compared with the teacher's argument to lay a conceptual foundation for comparing and applying to a new problem, which would trigger another round of an argument-versus-counterargument process to refine students' current conceptions of a physics concept under discussion.

Figure 1

The Reconstructed Illustration of Zhou's Figure 1(2010) The Argument Approach to Teaching Science



With the development at both the theory and application levels of conceptual change research, the 1990s saw a rapid field expansion. When compiling an inventory-like review of conceptual change studies in 2020, Canadian Franco-phone scholar Patrice Potvin commented, “the early ’90 s saw an ‘explosion’ of research propositions on the topic. It is possible that the initial publications on the topic (with the publications of special issues), triggered this apparent enthusiasm” (pp.174-175). The rise of conceptual change research has also been documented in another research bibliography compiled by German Scholar Reinders Duit (2009). One significant but not reviewed theoretical development in this period is the so-called warming trend in conceptual change. The move was initiated by Paul Pintrich, Ronald Marx, and Robert Boyle when they published *Beyond Cold Conceptual Change: The Role of Motivational Beliefs* *and Classroom Contextual Factors in the Process of Conceptual Change* in *Review of Educational Research* (1993). The omission is justified by its indirect relevance to the learning process and the lack of clear understanding regarding its connection to the cognitive and metacognitive processes that are activated during conceptual change. In other words, it may introduce an uncontrolled error term and its interactions with the domain-specific content information processing.

Two Major Shifts

After a period of ten years, the rising phase of the initial wave of conceptual change studies is complete, with modifications becoming increasingly prevalent. In addition to foregrounding the non-cognitive emotional aspect of concept change, two major shifts are apparent, which should not be ignored. First, in the early 1990s, cognitive ecology theorists published a revisionist view of conceptual change in the literature (Strike & Posner, 1992), calling for reconsidering the rapid expansion of conceptual change research. The founding theorists proposed revising the then-current theoretical landscape of conceptual change studies, overtly expressing their concerns over the initial conceptualization of the subject matter. In their own words:

> Critique of the (initial) theory
>
> A. The theory assumed that learners have well-articulated conceptions or misconceptions about most topics
>
> B. The theory was too linear
>
> C. The theory was overly rational (p.147)

Clearly, the non-verbal aspect of conceptual change has drawn the attention of the researchers, showing their realization of the importance of studying the not-so-well-articulated facet of conceptual change. But how to achieve that has been left unanswered. Both verbal and non-verbal aspects of conceptual change warrant further exploration. However, the popular linear thinking style in the past ten years may not be flexible enough to reveal the fundamental connection between these two aspects. Therefore, a new taxonomy of concepts and conceptual change should be introduced to enhance research in this area. In brief, the first shift has changed the tone of the rational and radical conceptual change perspective, explicitly drawing attention to non-verbal aspects of conceptual change while breaking away from the linearity assumption widely held before. However, these inadequacies were still discussed with an ideal student type: elite White college students. Rechecking this student population-related assumption is also important because what they bring to the science classroom often differs dramatically from the monolingual and no-study-permit-needed White students. Ignoring the non-typical students' cognitive structures and their information processing easily distorts the results of today's conceptual change studies.

In this aspect, a second shift is distinctive, which can be seen in Zhou's reassessment of the goal of science education and his argument for a new sociocultural perspective of conceptual change (2012). The renewed viewpoint of conceptual change sees "border-crossing" science students as unique knowledge seekers from various language and cultural backgrounds. Thus, their Western science learning may not always align with what her first language-based classroom environment had offered and reinforced in her mind. In addition, the theoretical shift has expanded the default definition of science students, which includes more non-typical science students in Canadian and American colleges and universities.

The problem of non-typical students' conceptual change has not always been a central issue for conceptual change researchers. Here, I first focus on a twofold distinction between conceptual change and conceptual advancement that Zhou (2012) highlighted for improving conceptual change studies in this direction. For him, Posner et al. (1982) aim to replace science students' pre-instructional cognitive ecology or intuitive understanding of the natural world for learning scientifically accepted ones. On the contrary, conceptual advancement is to make a co-existence status of misconceptions and scientific knowledge possible. In his work, he aligned his notion of conceptual advancement with the collateral learning perspective (Jegede, 1997). He illustrated the idea with his personal experience of commuting between Windsor (Canada) and an American city. The border-crossing experience is not interpreted "as a simple sum of the original A and B (city), but a combination of two" (p.119); Therefore, "a *third entity* or *third space* is necessary to guide our understanding of this topic" (p.120, original emphasis).

According to this updated inclusive view, "(s)tudent preconceptions are a product of their everyday culture plus traditional culture, both of which constitute their life-world culture" (p.117). To accommodate such an inclusive view, a hybrid learning space covering the above two cultures and science culture is the new reality for them. Therefore, in this hybrid living and learning space, the coexistence of contradictory conceptions is commonplace and should be expected rather than replaced. New learning and teaching strategies are needed in it for their conceptual advance. From this perspective, Zhou (2012) argued for a timely revaluation of the goal of modern science education and conceptual change, especially when more culturally and linguistically diverse students are seen in Ontarian science classrooms.

Similarly, Nashon, Anderson, and Wright (2007) introduced African philosophies' contribution to modern knowledge creation, retention, and implementation. After acknowledging the thematic information of "social order rooted in respect and tolerance" (p.1) in the Special Issue of Journal Contemporary Issues in Education, the authors concluded, “there is a uniting revelation that the African worldviews, ways of knowing and pedagogy, there is unity in diversity as an underlying principle in African thought” (p. 6). The culturally and linguistically diverse ways of knowing also invite further scholarly examination.

In summary, at least three flaws in the theoretical landscape of conceptual change research have been identified after a decade of intense research efforts. First, the not-so-well-articulated metacognitive aspect of the change process has been foregrounded, pointing to the direction of future research efforts. Next, the assumption of linearity has been identified as unreliable, implying the need to attend to non-linearity mechanisms. Finally, there is growing recognition of the importance of understanding the socio-cultural factors that impact conceptual change among culturally and linguistically diverse students in hybrid learning environments. This calls for further research to explore this previously neglected area in contemporary science education. All in all, a unifying theoretical framework addressing these flaws is still out of reach.

Focusing on Physics Concepts: Problem-Solving or Conceptual Change?

As the name PER reflects, the research field focuses on physics teaching and learning issues. A noticeable recent event in this domain-specific field is the editor Charles Henderson (2016) announced renaming the Journal *Physical Review Special Topics-Physics Education Research* to *Physical Review Physics Education Research*. The act of removing the phrase *Special Topic*, according to the editor, reflects a “growing body of knowledge produced by the physics education research community” (p. 010001). This fast-growing research field covers at least six lines of enquiries. They are (a) conceptual change, (b) problem enquiry-based approach to science education, (c) instruction and curriculum, (d) measurement and assessment,

(e) cognitive psychology, and (f) beliefs and attitude about science teaching and learning (Docktor & Mestre, 2014). Although PER researchers still maintain a keen interest in conceptual change, culturally and linguistically various science students are still put aside.

Another layer of meaning within PER is associated with the same word “science.” By that, I mean a seemingly invisible sense-making connection that couples science and mathematical thinking exists. This umbilical-like bi-directional connection distinguishes this natural philosophy-derived research from other types of studies. This unique bond points to a third knowledge matrix covering vectorial algebra, modern statistics, and their implementations in Physics. I keep on using the opening jigsaw puzzle as an example to illustrate this point. On the surface, different verbal, scientific, and mathematical levels are involved in characterizing a pendulum's oscillation period. To understand the descriptive and predictive information presented at these levels, a learner needs to understand the mathematical relationship between the verbal description of the period and the formula $T = 2\pi \sqrt{l/g}$. This formula represents the period, with "T" denoting the time it takes for a string or rod of length "l" to complete one full oscillation, given the gravitational acceleration "g." Understanding this relationship is essential for grasping the underlying concepts. Beneath the symbolic surface, the referent of the equation is a “simple” pendulum, which is an idealized mathematical construct but not simple at all. It is only with the aid of such a mathematical ideal that a physical pendulum’s motion can be understood. Furthermore, the isochrony of a simple pendulum motion is conditioned given a set of boundary conditions. One of them (its initial release angle) will be further explored later in experimental studies.

According to Docktor & Mestre (2014), “problem-solving researchers in PER often do not clearly define or draw upon a theoretical basis for their research studies” (p. 020119-7).

Seeing problem-solving as a multifaceted cognitive process, researchers holding the view tend to borrow from cognitive psychology, assuming a problem space that could represent a worked example in a learner's mind for further information processing.

The problem space in phycological theories is described as containing at least an initial state, intermediate steps, and a solution for representing physics problems. Within such a problem-solving mindset, a science student is viewed as a problem solver who mentally walks through the problem space, starting from an initial state, implementing intermediate moves, and arriving at a satisfying solution. In wandering such a mental space, memorized schema can be activated to facilitate or inhibit problem-solving. They are also interested in the transfer of problem-solving skills or domain-specific knowledge and metacognitive processes. To them, what is essential is the Western science community-endorsed problem-solving strategies and procedures, such as using the language of mathematics to solve physics problems or how novice college students become seasoned physicists by training through worked examples.

Side by side, the conceptual change theorists hold a different view of the learning process. They focus on science students' misconceptions instead. Borrowing from the Philosophy of Science and Piaget's cognitive developmental stages theory, they assume the role of a misconception replacement for improving students' science learning experiences. For them, their students walk into physics classrooms with a pre-instructional understanding of natural phenomena, such as believing that heat is a thing or that time and space are independent of each other. Such ideas and living experiences that seem to support such intuitions are deeply embedded in their knowledge system, which is incompatible with modern thermodynamic heat and special relativity theories. Changing their intuitive but science-incompatible conceptions are crucial to improving their learning experiences. Once they change their intuitive ideas, the notions of scientific theories will make sense to them. Previously reviewed conceptual change theories all originated from addressing such learning challenges, with the Accommodation view (Posner et al., 1982), Knowledge in Piece view (diSessa, 1993), and the Ontological Category view (Chi & Slotta, 1993) of conceptual change and other theoretical viewpoints included.

While the above theoretical perspectives may be sufficient for studying elite White monolingual students, they tend to overlook the cognitive reality of culturally and linguistically diverse students. Suppose conceptual change researchers genuinely believe that students' prior knowledge is key to their science learning. In that case, they cannot afford to ignore the impact of their unique information processing abilities, which are shaped by their experience with multiple languages. Take the group of study permit-defined international students as an example. Coming to study in Canadian science classrooms as a minority group, they bring a unique cognitive construct, with most aspects of their information processing influenced by their language and cultural backgrounds.

The literature has reported the language-enhanced and problem-solving-based curriculum in PER (Rillero & Hernandez, 2016). This type of PER study promotes “embedded strategies to facilitate ELL learning, including the introduction of new vocabulary, supporting writing for scientific purposes, and planning opportunities for small-group discussion” (p. 15). However, as pointed out by Zhou (2012), these scholars “actually reiterate the universal idea of Western science, knowingly or unknowingly” (p. 116). Without a fundamental understanding of these culturally and linguistically diverse students’ active information processing, it is easy to miss the opportunity to facilitate conceptual advancement in a meaningful way.

To understand the conceptual advancement of these students, I analyze their metacognitive processes, focusing on those that arise after learning a second language.

Metacognition was initially referred to as knowing or regulating a learner's cognitive processes (Bjork et al., 2013; Flavell, 1979). Later, Nelson and Narens (1990) characterized metacognition as a two-level construct: meta- and object-level. Between these two levels are monitoring (object-to-meta level) and control (meta-to-object level) processes. In this sense, a learner's metacognition "controls" her cognitive processes, whereas cognitive processes "report" to metacognition. In Zhou's argumentation for conceptual advancement (2012), these metacognitive processes are named as "meta-knowledge" (p.124) or as "a third entity" (p.120). They "might result in an even better understanding of both knowledge, their associated epistemologies, and limitations as well" (p.124). As in the case of conceptual change and problem-solving, metacognitive processes are constrained by what international students have learned before they walk into a Canadian science classroom, which is next summarized within a probabilistic framework.

A Recent Survey: Representative Voices in the Field

In a recent review of conceptual change theoretical models, a group of Canadian and Chinese scholars identified a downward trend in the whole field (Potvin et al., 2020). According to their summary, the early 1980s marked the onset of conceptual change theories. The first decade (1982-1992) saw its uprising trajectory. The next ten years saw "more value judgments" (p. 184) about these theoretical models and their empirical confirmations. At the turn of the 21st century, a few experimental studies appeared, ushering in another golden age of conceptual change studies in the mid-2000s. Then, it declined. However, as a research topic in learning sciences, the term conceptual change was still listed as one of the top three from 2013-2017.

In the same review, Potvin et al. (2020) concluded that there are significant players in conceptual change theories. They are (a) Posner's (1982) Conceptual Accommodation model, (b) Vosniadou's (1994) Framework Revision, (c) Chi et al.'s (1994) Ontological Category Shift, (d) Hewson's (1982) Conceptual Capture or Exchange, (f) Pintrich et al.'s (1993) Warm Conceptual Change, and (g) diSessa' s (1993) P-prim Reintegration. Posner's Conceptual Accommodation model and Hewson's Conceptual Exchange are the same among these models. Pintrich et al.'s (1993) Warm Conceptual Change model points to non-cognitive factors. The other three all turn to cognitive causal explanatory systems or metacognitive aspects of conceptual change. As introduced before, they lamented an apparent decline in conceptual change research.

To explain the downward spiral of conceptual change studies, they identified: (a) a transition from individual learning to more social and situated learning; (b) the complexity of conceptual change phenomena; (c) new frameworks rebranding existing ones. As for the individual-to-social learning transition, conceptual change research has been impeded somehow by a sterile debate arguing about individual students' learning progress or participation in social learning. However, the outlook of conceptual change studies may not be so pessimistic if a new taxonomy featuring a probabilistic dimension could be secured from the beginning because the notion of probability equally applies to both the intra- and inter-individual levels in terms of learning scientific concepts. I see this curious standoff as an invitation for a systematic retrospective examination of the theoretical basis of conceptual change research.

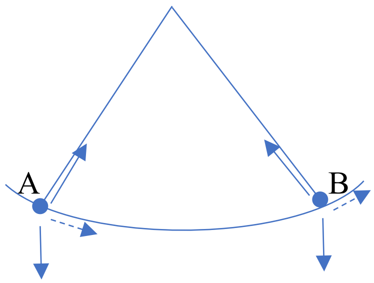
Illustration: A False Positive Identification of a Force in Pendulum Motion

To extend the opening illustration of solving a pendulum jigsaw puzzle with missing pieces, I considered a science education example that was embedded in a richer theoretical and experimental context: learning pendulum motion. For example, Colin Gauld (2004) published a reference list *Pendulums in the Physics Education Literature: A Bibliography*, where he traced the investigation of a simple pendulum motion back to 1939 and 1944. If the history of the so-called Western science was considered, Michael Matthews, in his article *Idealisation and Galileo's Pendulum Discoveries: Historical, Philosophical and Pedagogical Considerations* (2005), found roots of pendulum-related ideas in one of Galileo's letters dated 1632. It seemed four hundred years of time distance did not erode the learning enthusiasm surrounding this seemingly simple mechanic device.

In the context of describing students' misconceptions, John Clement documented in *Students' preconceptions in introductory mechanics* (1982) how the student conceptual primitive of the relationship between force and acceleration was misunderstood at the qualitative level in the context of a pendulum problem. The pendulum problem was designed to elicit the "motion implies a force" (p. 67) preconception (See Figure. 2).

Figure 2

The Pendulum Problem



The problem stated:

(a) A pendulum is swinging from left to right as shown below (above). Draw arrows showing the direction of each force acting on the pendulum bob at point A. Do not show the total net force and do not include frictional forces. Label each arrow with a name that says what kind of force it is.

(b) In a similar way, draw and label arrows showing the direction of each force acting on the pendulum bob when it reaches point B. (p. 67)

Facing such a pendulum motion problem, college students often drew the dashed line representing the driving force of the pendulum. In contrast, the physicist only labelled two types of forces as shown in the two solid lines: gravity and the tension force. For an illustration of the difference, the dashed line was added as evidence to show these students' preconception that "motion implies a force." The students believed that there must be an independent force acting on the bob in the direction of its movement. The 2 × 2 conceptual framework (hits, correct rejections, misses, and false positives) indicates that these students demonstrated a tendency towards false positives. Specifically, they added an extraneous "force" to the visual representation of the pendulum, in addition to the necessary tension and gravity. This non-existent intuitive force was seen as an "essential" component of the swinging pendulum.

Moreover, Clement (1982) summarized the common features of the "motion implies a force" preconception, such as the following:

(1) Continuing motion, even at a constant velocity, can trigger an assumption of the presence of a force in the direction of motion that acts on the object to cause the motion.

(2) Such invented forces are especially common in explanations of motion that continues in the face of an obvious opposing force. In this case the object is assumed to continue to move because the invented force is greater than the opposing force.

(3) The subject may believe that such a force "dies out" or "builds up" to account for changes in an object's speed. (p. 69)

In discussing the implications of such findings, Clement (1982) noted that the preconceptions are “not likely to disappear simply because students have been exposed to the standard view in their physics courses. More likely, Newtonian ideas are simply misperceived or distorted by students to fit their existing preconceptions” (p. 70). He further suggested Galileo might be aware of the teaching challenges faced by a modern physics instructor for “his dialogs represent a marvelous attempt to deal directly with the common preconceptions and prevailing theories of his time at a qualitative level… One might do worse than to take these aspects of Galileo’s teaching technique as a model for pedagogy today” (ibid).

Summarising the Qualitative Aspect of Conceptual Change Studies

The previous sections contend that conceptional advancement in domain-specific areas such as PER relates to at least the three strands of ideas: problem-solving, conceptual change, and international students’ unique information processing processes. As learning and cognitive processes are inherently probabilistic, it is essential to prioritize the uncertainty principle when studying conceptual change in the human mind. I followed Gigerenzer and Murray (1987) and Luce (1992) to construct a probabilistic framework for rethinking conceptual advancement. Specifically, I meant that the brain's information processing is probabilistic, whether in problem-solving, conceptual change, or metacognitive reflections. The creation of such a probabilistic framework of conceptual change processes was also informed by considering the brain’s structural plasticity and an innate ability to change itself through learning.

Among the possible outlooks of such a probabilistic framework, a psychologically realistic one is a human memory-oriented information processing mechanism, which involves memories’ activation, interference among what has been retrieved from memories, and their decay. From such a memory retrieval-based perspective, what has been described as problem-solving and conceptual change can be re-interpreted by a much simpler cognitive information processing mechanism: priming. In other words, what occurred in the past should influence what happens now and what will come next, showing the effects of working memories on (dis)organizing subsequent responses. The new probabilistic perspective suggests that science students' working memory mechanisms play a crucial role in their conceptual advancement in learning. Thus, from the new probabilistic perspective, science students' active memory or cognitive workspace affects their conceptual advancement in science learning. The new probabilistic framework has implications for its measurement, which is discussed in the next chapter.

CHAPTER 3 CONCEPTUAL CHANGE IN TIME: A SECOND HISTORICAL PERSPECTIVE

In the context of introducing how hard it was to measure time in history, Mathew (2000) notes that "(t)ime measurement, as distinct from timekeeping, could not occur until people thought time was something measurable" (p. 47). A similar lack of awareness of time measurement can also be said about the over forty years of conceptual change studies. As conceptual change research in science education advances from the late 1970s to the present day, researchers have tried various empirical methods for characterizing the dynamics of such a learning process. Most of them have relied on qualitative methods such as surveying, interviews, or a personal reflection of a learning experience (Moore & Dawson, 2015; Posner et al., 1982b; Tseitlin & Galili, 2005; Tamayo Alzate & Sanmartí Puig, 2007; Zhou et al., 2008). Such methodological choices assume that the temporal aspect of conceptual change processes can be expressed in words or estimated but not measured. However, change occurs in time or implies time. If this is the case, no exception should be made to understanding conceptual change. The question is how time as a dependent variable can be made explicit.

Turning to quantitative methods in science education, a few researchers have attempted to introduce precise time measurements for studying conceptual change rather than just coding verbal or nominal data (Babai, et al., 2006a; Potvin, Masson, et al., 2015). Despite the significance of this type of study, there has been no review that critically synthesizes such measuring efforts. To fill the gap, I conducted a critical interpretive synthesis (CIS) of this unique set of experimental studies featuring the temporal aspects of learning physics concepts. CIS was chosen because it combines the synthesis of both quantitative time measurement and qualitative timekeeping or estimation data, which was deemed suitable in this case. The synthesis was guided by the following question: How is time, an essential aspect of conceptual change, operationalized and measured in conceptual change research? One particular aspect of asking such a question deserves to be highlighted: the operationalization, though being "condemned" as a positive dogma in education studies, offers a method of differentiating daily timekeeping or rough time estimation from precise time measurement, a key point needed to understand conceptual change.

To clarify an emerging tie between time measurement and conceptual change in science education, I briefly describe how conceptual change studies took their form in a philosophical tradition barely noticing time. Next, another time-honoured mental chronometric tradition was traced, highlighting a notion of time as a factor measurable. Then, I critically synthesize a decade of conceptual-change-in-time studies, showcasing their ranges and significant results. What follows is a focused critical assessment of the negative priming procedure of this type, addressing its reliability and raising methodological and theoretical concerns. Finally, I summarize the synthesizing arguments and recommend the next move. Overall, I set myself in the mood of communicating with science teachers and researchers who might be interested in but unfamiliar with or still skeptical about adopting the experimental paradigm of this type, addressing their concerns and explaining how and why the paradigm has come to be appealing in conceptual change research.

A Philosophical but Atemporal Origin: Qualitative Conceptual Change Research

In general, conceptual change refers to dramatic perceptual and theoretical (re)transformation in the mind. Within science education, the same term denotes a learning process in which a student's preconception of some aspects of the natural world shifts or turns into a new scientific one. This teaching and learning-related sense has a philosophical origin, but time has not been a significant factor considered during the early days of establishing the field of study. From the late 1950s onwards, the philosophers Thomas Kuhn (1970), Stephen Toulmin (1972), and Imre Lakatos (1970) jointly drew public attention to how a new scientific theory would replace a previously legitimate scientific one over time in history. The problem was attributed to ambiguous uses of the term conceptual change to some extent. For some, it refers to a conceptual overhaul of a theoretical structure. In contrast, for others, the same term speaks of a psychological process that occurred in a researcher's mind, with two incompatible perceptions settling down to a coherent, rational interpretation.

For example, viewing the same Necker Cube (a line drawing of two overlapping cubes) often leads to two visual perceptions: a cube protruding leftward or rightward. Neither is totally right or wrong, only suggesting a consistent influence of memory or prior knowledge on current perception. After reflecting on similar phenomena, Kuhn (1970) introduced into the philosophy of science what is now known as a paradigm shift for explaining a scientific revolution, such as replacing the phlogiston theory of fire with its oxidization process conception. In essence, the normal course of scientific development can be dramatically transformed after responding to a crisis or anomaly of a scientific theory, thus leading to a paradigmatic change. After the change, scientists equipped with a new paradigm would view and explain the same phenomenon differently from their predecessors. Swiftly, Kuhn's influences have extended beyond the philosophy of science.

In the late 1970s and through the 1980s, the time-out-of-the-equation signs of such philosophical influences can be easily spotted in science education literature. For example, Hewson (1982) reported a case study exemplifying his conceptual capture that characterized a reconciliation of a new conception with prior knowledge. Moreover, Nussbaum and Novick

(1982) documented another case study of two lessons on particle models, illustrating the effectiveness of accommodating students' alternative frameworks. Commonly, they suggested a theory of conceptual change for learning a counterintuitive scientific idea. The same suggestion has also been made simultaneously by Posnerey al. (1982). They drew a parallel between conceptual change in students' learning and Kuhn's paradigm shift (1970). Built on this analogy, they suggested four time-insensitive conditions that might help enable a student's conceptual change in learning: (a) a dissatisfaction with existing conceptions by students; (b) a new intelligible alternative for them; (c) the plausibility of the alternative; (d) its fruitiness. In their view, students' prior knowledge (conceptual ecology) would determine the direction of a conceptual accommodation if these conditions can be met. The implications of such a conceptual change theory for educational practice were also elaborated elsewhere by Strike and Posner (1982).

As a result, the discussions have marked a philosophically induced origin of conceptual change studies but are atemporal. Alternatively, it can be said that the temporal aspect of conceptual change, in the eyes of early theorists, has been simplified or estimated as a linear, staged one: moving from a stage of the feeling of dissatisfaction to another one of accommodating a new science concept. However, time is an essential aspect of change, whether physical or psychological.

Another Time-Honoured Tradition: Mental Chronometry in History

Although any physical change in the world occurs in time, and scientists are experts in quantifying such a duration, it is still a moot point how to conceptualize and measure a learner's conceptual change in time. To some extent, the awkward situation mirrors a significant historical event when the late 19th century scientists were finally approaching the threshold of a breakthrough in realizing there is a speed limit to human information processing. It was in the last quarter of the 1800s that time, as a fundamental fabric of human experiences, finally became a new frontier for scientific exploration, though it had escaped so many philosophers and scientists' great minds for over a thousand years. Given that this realization is the basic rationale for measuring conceptual change in time, it merits tracing its origin.

In the early 1820s, astronomers were among the first researchers who had noticed the individual temporal judgment differences. According to Meyer et al. (1988), Bessel formulated the personal equation in 1823; but his voice went unnoticed. The circumstance remained the same until the German physicist and physiologist Hermann von Helmholtz (1850/1853), who first measured the propagation speed of neural signals, revealing a finite nerve conduction velocity roughly from 25.0 to 42.9 meters per second (Jensen, 2006; the rate varies from 0.5 to 90 m/s as we now estimate). This fact of a finite speed means that what we see or hear is slightly delayed relative to the presence of external stimuli. In Boring's (1957) words, the realization "brought the soul to time," ushering in a golden age of chronometric research.

Given the realization of the potential for measuring mental activities, researchers of the late 19th century sought to obtain and interpret the time lag between the presentation of external events and the onset of a response to the task-relevant stimulus. This duration was named *reaction time* by Sigmund Exner, an Austrian physiologist (Jensen, 2006), in 1873. Regarding its experimental applications, the Dutch physiologist Frans C. Donders (1818-1889) first demonstrated how to obtain a reaction time difference by subtracting a simpler form of the duration from a more complex one in his subtraction method. That is to say, a simple reaction time of one sensory input and one motor output can be subtracted from a complex one involving more stimuli and selecting one of the two responses. The difference can thus be interpreted as the duration of the selection.

Following Donders' demonstration, researchers of the 19th and 20th centuries saw the ups and downs of such an endeavour, stretching the reaction time-based research enterprise from a Golden Age (1850 – 1900 A.D.) to a Dark Age (1900 – 1950 A. D.) and its Renaissance (1950 A. D. to present) (Meyer et al., 1988). When cognitive psychology gradually came to the front stage in the 1970s, mental chronometric measures were recast to tackle human information processing's underlying psychological mechanisms, with their impact still felt today. For contemporary readers, modern mental chronometry (1988) is a general term for a range of empirical time measurement paradigms in obtaining and analyzing behavioural measures, such as reaction or response time, response accuracy, and speed-accuracy trade-off. Against such a background, the emergence and development of conceptual change in time can be put into perspective, especially showing conceptual change with other variants of simple reaction times (Potvin, 2013; Potvin, Sauriol, et al., 2015).

One implication of the 19th century discovery is that time has finally become essential in the foreground of researchers' attention, especially for characterizing mental processes. With the establishment of experimental psychology, mental chronometry ushered in its golden era. The moral of this story for science education is that there is no reason to keep conceptual change studies out of the reach of such a scientific endeavour. In such a spirit, a few open-minded science education researchers have focused their attention on a new direction.

A Methodological Turn: Measuring Conceptual Change in Time

Turning to mental chronometric methods marks the beginning of time measurement of conceptual change in science education. The turn helps make explicit the notion of time as a measurable factor, extending the mental chronometric tradition. Babai et al. (2006), for example, designed a reaction time study to examine conceptual change in time. In this case, the student's performance was measured by comparing the participants' choice reaction times of judging areas and perimeters, which marked the duration from the onset of presenting a visual pattern to the initiation of such a choice. After comparing the averaged durations of students' performances driven by intuitive or counterintuitive rules, they observed a reaction time difference: about 360 milliseconds, roughly one-third of a second. Though brief, this type of evidence significantly differs from verbal responses and personal reflections documented in the literature.

First, such a real-time measure is an online index of conceptual change, thus characterizing the change process when its temporal unfolding is still alive in a learner's mind. Moreover, it does not require participants to verbalize their learning experiences consciously, thus digging deeper into cognitive processes. Thirdly, it generates quantitative data at the ratio level contrasting nominal or verbal responses, thus affording uses of advanced statistical analyses. In sum, an interactive dynamical mechanism underlying conceptual change is operationalized and measured through the lens of modern mental chronometry, showing a combined effect of attention and memories. In response to such a methodological turn, other researchers have followed the lead, generating a small but unique body of research literature featuring the conceptual change in time.

A Decade of Measuring Conceptual Change in PER

Inspired by Babai et al.'s (2006) demonstration, researchers have generated a unique set of mental chronometric results of conceptual change. To address the research question on such time measurement, I conducted a systematic literature search using the following search inclusion criteria: (a) must include conceptual change as a keyword or appear in the abstract, (b) must include a baseline level, (c) must include an experimental design showing priming techniques with independent and dependent variables and the control conditions specified, (d) must record priming effects in conceptual change regardless of the direction of priming effects, and (e) must report methods and results in English.

The following keywords were included in the search because they adequately capture the theoretical and empirical aspects of the questions of interest. They were: conceptual change, priming, reaction time, misconception, conceptual ecology, knowledge structure coherence, and science education. The Boolean connector AND was used to connect conceptual change and priming; the connector OR was also included to link other combinations. These keywords were submitted to the following academic databases: Web of Science, JSTOR, ERIC, PsychINFO, ProQuest Dissertations & Theses, and Google Scholar. The databases cover most peer-reviewed, high-quality publications. In addition, the reference lists of the returned results were scanned for more information.

The search results are summarized in Table 1. Commonly, they set up at least two experimental conditions to contrast the students' reaction times. The Table shows that at least three types of conceptual change in time can be identified considering how the researchers have established their experimental procedures. They are (a) the simple choice reaction time paradigm (Babai & Amsterdamer, 2008; Potvin, Sauriol, et al., 2015; Vosniadou et al., 2018); (b) the negative priming procedure (Potvin, Masson, et al., 2015); (c) brain imaging (Zhu et al., 2019) with reaction time recorded. Only the first two categories will be discussed in detail for this synthesis. The third one is irrelevant due to the limited time resolution of fMRI results (Zarahn, 2000).

Table 1

Reaction Time in Conceptual Change (2006-2019)

Article	School Subject	Focused Concept	Paradigm	DVs	Participants
Babai, R., et al. (2006)	Mathematics	The perimeter of a shape	Comparison	RT & Accuracy	68 Students (G11)
Babai, R., et al. (2006)	Probability	Drawing likelihood	Comparison	RT & Accuracy	22 Students (G11 & 12)
Babai, R., et al. (2008)	Physics	States of matter	Classification	RT & Accuracy	41 Students (G9)
Babai, R., et al. (2010)	Biology	Living and non-living objects	Classification	RT & Accuracy	58 Students (G10)
Babai, R., et al. (2012)	Mathematics	The perimeter of a shape	Comparison	RT & Accuracy	51 Students (G11-12)
Potvin, P., et al. (2015)	Physics	Weight of objects	Negative Priming	RT & Accuracy	565 Students (G5-6)
Potvin, P., et al. (2014)	Physics	Buoyancy	Negative Priming	RT & Accuracy	128 Students
Potvin, P., & Cyr, G. (2017)	Physics	Buoyancy	Forced Choice	RT & Accuracy	62 Preschoolers, 557 students (G5 & 6), 22 teachers
Roell, M., et al. (2017)	Mathematics	Decimal number	NP	RT & Accuracy	26 Student & 37 Students
Van Hoof, J., et al., (2013)	Mathematics	Fraction	Comparison	RT & Accuracy	129 Students
Vosniadou, S., et al. (2018)	Science and Mathematics	Force, Volume, and fraction	Recategorization Sentence Verification	RT & Accuracy	133 Students (G 4 & 6)
Zhu, Y. et al. (2019).	Physics	Electricity	ERPs	RT, Accuracy, & ERPs	27 Undergraduates

Note: DV means the dependent variable, and G in G5 is for Grade.

The procedural differences can be attributed to researchers' theoretical considerations of conceptual change in each case. For example, Babai et al. (2006) were interested in measuring "the immediacy characteristics of intuitive responses." To show the immediacy of engaging intuitive rules, they designed a comparison task in which the students were invited to judge the areas and perimeters of geometrical shapes. According to their immediacy hypothesis, intuitive rules like "more A mean more B" would engage first and drive the reasoning. Otherwise, in a condition requiring students to take a second look at the visual stimuli, it would take longer to start counterintuitive rule-based reasoning.

As expected, the observed reaction time differences did confirm such a prediction. That is to say, the average reaction times of the choice driven by the intuitive reasoning were on average shorter than those driven by the counterintuitive ones. Given the revealed temporal pattern in science and mathematical reasoning, they put forward their Intuitive Rules theory for an explanation. Later, they applied the same experimental technique to other conceptual change studies in Physics (Babai & Amsterdamer, 2008), Biology (Babai et al., 2010), and Statistics (Babai, et al., 2006).

Rather than studying the temporal effect of using intuitive rules, Potvin (2013) synthesized new findings on how the brain works and the latest results from reaction time studies to propose a new conceptual change theory based on the prevalence model. It is a proposal that favours: (a) an initial availability of a target concept, (b) an installation of inhibitive "stop" signs, and (c) a durable and conceptual prevalence of the target concept. However, the effectiveness of the prevalence model of conceptual change has yet to be tested empirically.

Two years later, Potvin and his colleagues (2015) introduced another variant of reaction time study - the negative priming paradigm - into science education. For example, in a study of objects' buoyancy, Potvin et al. created different levels of conceptual conflicts and measured their corresponding effects on the performances. They claimed to have documented graded reaction times and a significant negative priming effect, given what they had observed in the experiment. The negative priming effect was interpreted as the scientific evidence showing mental efforts in inhibiting concurrent conceptual interference, thus supporting their prediction derived from the persistence model.

Similarly, Potvin and other researchers applied the negative priming-based approach to a second expanded study of buoyancy (Potvin & Cyr, 2017) and investigated objects' weight (Potvin, Sauriol, et al., 2015). Out of these efforts was a reaction time-based negative priming phenomenon associated with the conceptual change processes. Consistently, they interpreted the results as confirming their predictions derived from their conceptual prevalence model rather than the original conceptual change one with a misconception being replaced (Posner et al., 1982).

In 2018, Stella Vosniadou and her collaborators conducted a comprehensive study featuring a comprehensive set of test batteries and classic experimental paradigms in psychology. They also devised a set of real-time experiments to test the hypothesis, assuming the functional role of executive mechanisms in determining conceptual change. From their perspective, students' executive function of shifting and inhibiting interfering effects of a conflicting preconception was the key to effective science teaching.

As expected, the results confirmed that inhibition was engaged to constrain a competing preconception's interfering effects. Once again, they argued for the idea of a co-activating preconception in the change process and against that of a total replacement. This sizable body of conceptual change experimental studies seems to suggest that students' intuitive preconceptions can not be replaced by scientific ones because the temporal aspect of conceptual change has shown its effects in time.

However, it is still too early to rush to such a conclusion. The observed reaction time differences may be the most explicit part of their studies, but they are only the visible tip of the whole mental chronometric tradition (Jensen, 2006; Menon, 2012; Meyer et al., 1988; Posner, 2005), which is much deeper, broader, and more complicated than the surface events can tell. Beneath the experimental procedure is an extensive theoretical foundation that associates early astronomers' efforts in understanding personal equations and psychologists' perspectives in investigating human information processing. To the extent that researchers ignore such a theoretical foundation, simply equating a reaction time difference with a time interval, they hold back meaningful advances in understanding conceptual change.

Negative Priming Elsewhere: An Index of Inhibition?

In science education literature, negative priming has been interpreted as inhibiting the interfering effect of students' misconceptions. However, the same phenomenon has also been studied elsewhere (Neill & Valdes, 1992; Tipper, 1985). For experimental psychologists, they have come up with alternative explanations. For them, the term *negative priming* speaks of a special repetition effect, mostly when a current target stimulus represents some features of a previously ignored distractor. For example, a learner may become slower or error-prone when trying to re-engage in intuitive reasoning after learning a correct counterintuitive one. The performance degradation can be shown by recording a slower response or a higher error rate, thus negative priming. It was coined by Tipper (1985) when he introduced a variant of the

Stroop-colour-word naming paradigm (Stroop, 1935; Macleod, 1991). Since his introduction, the negative priming paradigm has been widely used to show how humans' selective information processing is impeded by what has happened before.

This experimental procedure has an indispensable design feature that couples a posterior response with its prior and unattended exposure event. Such a prior-to-posterior repetition structure enables psychologists to examine sequential aftereffects of visual or auditory information processing. The negative priming magnitude is roughly 20 to 100 milliseconds, much shorter than those reported for conceptual change studies.

What could explain the duration magnitude difference of the same phenomenon? Cognitive psychologists have proposed selective inhibition and memory retrieval mechanisms for their explanation from an information processing perspective. In the 1980s, the dominant explanation of negative priming was the principle of selective inhibition. That is to say, a delay ought to be observed in performance when actively inhibited information is to be re-used again. The reason is that this mental representation has been inhibited before. However, in the two 1992 papers, Neill and colleagues (Neill et al., 1992; Neill & Valdes, 1992) proposed an alternative account of the same phenomenon: episodic retrieval. According to the new account, the processing of a target can trigger the retrieval of the initial binding information associated with the distractor in memory, and such retrieval causes a delay in performance, not selective attention-related mechanisms.

Although it is still controversial about what might give rise to the reaction time differences, it is now clear that selective inhibition and episodic memory retrieval are not necessarily exclusive to one another. Therefore, negative priming in psychology literature, on the one hand, might be caused by the attentional mechanism in spatial tasks, given that selective inhibition is required. On the other hand, the same effect can also result from memory-based factors in meaning-related responses. More than these two accounts, a multiple-process view of negative priming has also been proposed (D'Angelo et al., 2016). Although the experimental techniques are the same, their uses in psychological studies and conceptual change research have developed independently in the two fields. To some extent, science education researchers borrowed the techniques but did not look at the lessons learned elsewhere. Next, we turn to their connections and critically evaluate conceptual change in time.

A Critique of Negative Priming of Conceptual Change in Time

Both cognitive psychologists and science education researchers are interested in studying the consequences of overcoming concurrent mental competition with the negative priming paradigm. While the former uses it for examining basic attention and memory-based processes, the latter has applied the procedure for science teaching and learning scenarios. Their implementations have covered from thinking with intuitive mathematics (Babai, et al., 2006) to studying scientific ideas in physics, such as states of matter (Babai & Amsterdamer, 2008), the weight of objects (Potvin, Masson, et al., 2015), buoyancy (Potvin, Masson, et al., 2015; Potvin & Cyr, 2017), force (Vosniadou et al., 2018), and in biology (Babai et al., 2010). Their experimental designs have evolved from using simple reaction times-related measures to implementing the negative priming paradigm (Potvin, Masson, et al., 2015). In doing so, they have overcome the limits of only relying upon verbal descriptions and personal reflections to capture the change in reaction times, accuracy rates, and reaction time differences.

While applauding their contribution to introducing modern mental chronometry to conceptual change studies, there are concerns about implementing the negative priming paradigm. There are at least three types of concerns: (a) the reaction time reverse inference problem, (b) the design issue, and (c) the concerns of the statistical analyses. More importantly, science education researchers may have misread the negative priming procedure, ignoring its theoretical basis. Although these comments have focused on implementing negative priming in conceptual change studies, similar considerations can also be said for the premature use of mental chronometric measures in general for science education research.

As introduced earlier, when mental chronometric measures were first introduced to science education, Babai and his collaborators (2006) relied on the following reasoning: the intuitive reasoning would be faster while the counterintuitive reasoning ought to be slower; therefore, a selection driven by an intuitive reasoning process should have a shorter reaction time than that by a counterintuitive one. From their perspective, they were meant to measure the immediacy of using intuitive rules. There is no quibble with such an application of the chronometric method. Researchers have reversed this logic in recent years, using reaction time differences to argue for the unobservable persistence of preconceptions and various levels of interference caused by activating such preconceptions (Potvin, Sauriol, et al., 2015).

However, this is a step jumping too far from its empirical basis because reaction time differences have been associated with episodic memory retrieval mechanisms elsewhere (Neill & Valdes, 1992). In short, there is a key contrast between the logic that intuitive reasoning occurs faster than a counterintuitive one and its reversal: identifying a faster response only with an intuitive reasoning conception because the reaction time is shorter. The reversal is problematic because it is known that various cognitive processes contribute to reaction time differences (Neill & Mathis, 1998; Tipper, 2001). There is no easy way to attribute the difference to inhibition in mind only. Moreover, the subtraction method-based interpretation of reaction time differences has already been challenged by psychologists (Meyer et al., 1988). In this sense, any inference based on such differences must consider the already-identified memory processes and their related methodological concerns (Kane et al., 1997; Longstreth, 1984; May et al., 1995; Milliken et al., 1998).

Besides the reaction-time reverse inference problem (Krajbich et al., 2015), it seems that the initial evidence of negative priming in conceptual change was obtained by misreading a proper experimental procedure. Typically, a unit of negative priming consists of two parts: (a) a prime with a distractor and (b) a subsequent probe repeating its immediate leading distractor as a probe target. In most cases, its design matrix resembles a 2 x 2 grid, with the element in each cell serving a different function. The most critical part of such a procedure is a match between a prior distractor and a posterior probe target. However, these characteristic features can not be found in extant conceptual change experimental studies.

Instead, in one study, there were 216 stimuli presented to each participant in a random order (Potvin, Masson, et al., 2015), and the prime-to-probe relation was only re-established after their data collection through data resorting by a computing device. This procedure may have missed the critical point of using the experimental measure to control irrelevant variables' unwanted effects. More importantly, what has been missed in the design stage can not be compensated by later statistical measures.

Also, a researcher can not simply analyze them by averaging data across trials because reaction time data may contain systematic variability and noise. In this aspect, relying too much on mean reaction times may easily introduce unwanted biases into the discussion and result in a misinterpretation of what has been observed in conceptual change studies. As the mental chronometry tradition has shown to us, a simple reading of reaction time differences, without considering specific theoretical assumptions about the underlying psychological processes (selective attention or memory retrieval), easily leads to deceptive results (D'Angelo et al., 2016b; Frings et al., 2015; Meyer et al., 1988).

To date, a comprehensive theoretical framework of conceptual change in science education is still out of reach. The lack of a theoretical consensus on conceptual change has also led to other concerns. For example, Zhou (2012) put forward a cultural perspective of conceptual change in science education to challenge the replacement perspective of such change. According to this view, "(s)tudent preconceptions are a product of their everyday culture plus traditional culture, both of which constitute their life-world culture" (p. 117). Therefore, a hybrid learning space covering these cultures is the reality for science students. If viewed from this perspective, the co-existence of contradictory conceptions is normal and should be expected. Similar theoretical explorations may also help clarify the dynamics of students' conceptual change processes if further tested with mental chronometric methods.

In summary, some difficulties may impede a better understanding of conceptual change in time. Among these concerns, the reaction-time reversal inference problem has its own risks in only seeing the inhibitive aspect of conceptual change. More serious is a misreading of the typical negative priming procedure, which often requires a critical match between a prior distractor and a posterior probe target. Furthermore, some researchers may have ignored the theoretical concerns learned from the history of mental chronometry regarding handling mean reaction times and a recent theoretical move toward a cultural reassessment. Given these concerns, extant conceptual change studies (Potvin, Masson, et al., 2015; Potvin, Sauriol, et al., 2015; Potvin & Cyr, 2017) must be read more carefully, calling for further improvement and more meaningful replications.

Illustration: Error Terms in Measuring Pendulum Motion

To further extend the illustration of pendulum motion, I briefly summarize the quantitative aspect of learning pendulum motion, following the experimental tradition in science education. César Medina, Sandra Velazco, and Julia Salinas of Argentina (2004) documented their discovery of *Experimental Control of Simple Pendulum Model*. The following aspects of the pendulum were analyzed quantitatively: “vanishing friction, small amplitude, not extensible string, point mass of the body, and vanishing mass of the string” (p. 631). To do this, their students had to construct a simple pendulum that approaches an ideal one so that the student in a physics laboratory session could analyze the model assumptions which influence its oscillation period. In their own words,

a) Physical pendulum period

$Tp = 2\pi \sqrt{I / mgd}$ (1)

where Tp represents the period of the physical pendulum, *I* the moment of inertia, *m* the mass of body, *g* the acceleration due to gravity and *d* the distance between the axis and the center of gravity of the system.

b) Ideal simple pendulum period

$Ts = 2\pi \sqrt{l/g}$ (2)

where *l* is the length of the string.

Equation (1) was deduced assuming:

A1: negligible friction (the resultant torque on the system about the horizontal axis is solely due to the weight of the body).

A2: small oscillation amplitudes (in the equation of motion, the sine of the amplitude angle can be replaced by the angle in radians).

A3: the pendulum is a rigid body (invariable mass distribution, constant moment of inertia).

…

A4: the string mass must be negligible.

A5: the body mass must be concentrated at a point. (Medina et al., 2004, p. 632)

After showing how a physical pendulum can be mathematically associated with an ideal one, they used a section focusing on error analysis. From such a viewpoint, there are random errors in addition to a systematic error due to "the fact that assumptions A1 to A5 are not fulfilled" (Medina et al., 2004, p. 633). In particular, these error terms include the fluctuations "due to friction (ε_f), initial amplitude (ε_α), variable length of the string due to a variable tension during oscillation (ε_T), mass distribution of the body (ε_b), and mass of the string (ε_s)" (Medina et al., 2004, p. 633). With the analysis of error considered, they showed that the model assumptions could be accomplished in laboratory exercises within a reasonably small range of experimental errors. They concluded that,

> Considered separately, within an error of 1%:
>
> – an initial amplitude of 23° is "small".
>
> – a sphere, whose diameter is 30% of the length of the string, is "a point mass".
>
> – a mass of the string equal to 10% of the mass of the body is "vanishing".
>
> – any elastic elongation suffered by the string during the static process of loading is negligible, providing the string length is measured after the loading.
>
> – without loosing its property of 'not extensible', the string may vary its length during oscillation (due to a variable tension), providing this variation is less than the measurement error of the string length. (Medina et al., 2004, p. 639)

In their view, such a quantitative laboratory experimental demonstration advances a better understanding of scientific practices, promoting a deeper comprehension of the pendulum motion-related physics concepts. Moreover, the epistemological implications of the analysis of errors are also rich.

Summarising the Quantitative Aspect of Conceptual Change Studies

To bridge the mental chronometry and science education, Potvin and his collaborators (Potvin, 2013; Potvin, Masson, et al., 2015; Potvin, Sauriol, et al., 2015; Potvin & Cyr, 2017) have made systematic efforts to adapt the negative priming paradigm to conceptual change studies. However, such an adaptation for science education is still facing many challenges. Unaddressed methodological and theoretical issues must be noticed to advance the understanding of conceptual change.

At the method level, a careful reading of the priming literature and the proper use of experimental design can quickly solve the design problem. With a well-balanced design, unwanted influences caused by the irrelevant aspects of a task choice can be cancelled out. Moreover, a standard negative priming design would help other interested researchers replicate and extend what they did to obtain the conceptual change in time.

Also, given the experimental design structure, statistical analyses can be planned in advance with a pre-defined data analysis protocol. In so doing, they can serve either as a confirmatory means or an exploratory one. Only in this way, the analyses of variances would help a researcher tell whether what she has observed is a genuine effect or is caused by chance. Before running a statistical procedure, data screening is another cautious step, which has become a not-so-challenging task with modern statistical software packages.

The reaction-time-reversal inference problem is more serious. As it turns out, Potvin et al. (2015) noticed the memory retrieval account of negative priming. However, their discussion of the negative priming results barely mentioned the episodic binding-related factors. It means they may have exaggerated the empirical support for their persistence claim, which can be improved by considering the alternative interpretations. Moreover, the lessons learned from modern mental chronometry should also be considered for dealing with the reverse inference problem.

After a decade of studying conceptual change in time, a new empirical basis has been established to further reveal the dynamics of conceptual change through the lens of human reaction times. With reaction time and accuracy data on our hands, more valuable information on conceptual change can be collected, enabling extracting valuable information beyond a pure heuristic nominal description of the process. However, even with careful experimentation, some twists and turns are inevitable. Studying conceptual change in science education is not a plug-and-play act, just as the history of mental chronometry in this critical interpretive synthesis has shown us. Nevertheless, meaningful progress in this field can emerge through ongoing and rigorous conceptual change studies.

CHAPTER 4 THEORETICAL FRAMEWORK: ACTIVE LEARNING WITH A PROBABILISTIC FRAME OF REFERENCE

A key message from the qualitative and quantitative literature reviews is the necessity of developing a new conceptual framework abstract enough to explain both verbal and non-verbal aspects of conceptual change studies. Ideally, the conceptual skeleton would enable a researcher to gain a cognitive "foothold" in her conceptual space to overcome the identified three flaws of current conceptual change research while balancing the need to interpret the full range of empirical data documented so far. In this chapter, I present a new taxonomy of concepts and a learning mechanism to approach gaining such a theoretical position.

Breaking away from the perceptual similarity-based definition of concepts toward a new taxonomy of concepts is an unavoidable move in PER because modern physics concepts are highly mathematized and intended to explain experimental data. These features of the physical sciences have made the domain-specific knowledge so abstract that their conceptual similarity can only be found at the mathematical level. A twenty-first-century learner must come to terms with such a characterization to better understand a physics concept and its role in constructing a physics theory. The Newtonian conception of motion (Zhou, 2010) or the chemist's theory of acidity (Thagard, 1990) are such examples.

Building a new theory of this sort means oversimplifying the complex phenomena of conceptual change learning. However, such an idealization process has been essential since Galileo's time, with abstracting pendulum motion as an outstanding example (Matthews et al., 2005). Following such an idealization tradition, I propose a set of carefully selected theoretical elements appropriate for studying the conceptual change in students' conceptual spaces. The initial set of theoretical-constructing components includes:

1. Cognitive knowledge structure: a binomial distribution-like of the intuitive and counterintuitive conceptions with an overlapping middle area represented in a learner's conceptual space,

2. Possible learning outcomes: a 2 × 2 learning output grid driven by such a knowledge structure distribution,

3. Psychologically plausible learning mechanism: a time-based active sampling and decision-making process,

4. Types of anchor physics concepts: a new taxonomy of concepts and conceptual change with a probabilistic frame of reference.

Together, these four anchor assumptions structure a new type of conceptual change theory. At its core is an appreciation of a random variable's probability mass function (for a discrete rather than continuous random variable). The distribution of the function provides an entry point into a psychologically plausible mechanism of conceptual change. When measured in time, the change process results in a 2 × 2 learning output grid. The miss, false positive, hit, and correct rejection help tease the time courses of underlying (meta-)cognitive processes. The design of a sampling and decision-making-based learning mechanism offers a broader, yet precise, lens through which to view the fine-grained human information processing at the millisecond level that has only been occasionally explored in the past.

A Binomial Distribution of Intuitive and Counterintuitive Knowledge

Students often rely on their pre-existing intuitive knowledge, sometimes leading to incorrect responses even when they have learned the correct scientific concepts. For example, Clement (1982) found that students may mistakenly identify forces such as the force added to gravity and the tension force when analyzing pendulum motion. These intuitive responses persist even after students have been taught the correct scientific principles. Mathematically, such an overlapping scenario can be abstracted as a binomial sampling distribution which generates false positives, hits, correct rejections, and misses. The index of accuracy or error rates in a series of experimental trials can measure these responses. More specifically, a binomial distribution of a random variable can be viewed as a model for the number of correct responses in a fixed number of independent trials, where p represents the probability that a response may be correct on each attempt.

In conceptual change studies, this implies that a learnt or changed conceptual structure is more likely to lead to more correct observable responses. In contrast, an unchanged one keeps such a possibility at the control level. Thus, the probability p of h correct responses in n independent experimental trials could be assumed to be given by the following binomial probability mass function (for a discrete rather than continuous random variable):

$$f(h, n, p) = \binom{n}{h} p^h (1-p)^{n-h}, \; h = 0, 1, 2, \ldots, n \quad (1)$$

In the above formulation, the probability of success is assumed fixed. However, it is often desirable to model this as a function of other predictors. When learning a scientific concept, a student may use a pre-instructional but incorrect intuition or switch to a correct one. Such a change in the conceptual structure determines how likely the student would respond in a series of trials. When the correct responses as the dependent variable are considered for (dis)confirming an underlying conceptual change status, the responses can be characterized either as a varying continuous accuracy rate or a binary one with two discrete values. For the former, the Analysis of Variance (ANOVA) methods are often used to tell apart the conceptual item level and the participant-level variances for a group means comparison. For the latter, another type of statistical approach is preferred, such as logistic regression, which can estimate the probability of a student choosing a correct answer as a function of the conceptual change status.

There are two more essential characteristics of the logistic regression approach. First, it is built upon the notion of odds, defined as the ratio of the probability of an event occurring relative to its probability of non-occurrence. Second, as its name suggests, a logistic regression equation is expressed as the logarithm or natural logarithm of odds: ln(odds). In a general form, it is written as:

$$\ln(odds) = \ln\left(\frac{p(x)}{1 - p(x)}\right) = \alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_q x_q \qquad (2)$$

where the parameter α represents the logarithm of the odds of the baseline condition and each coefficient parameter β_k represents the natural logarithm of the odds ratio for the k^{th} predictor variable, x_k ($k = 1, \ldots, q$). This natural logarithm of odds ratio-based probabilistic framework is well-suited for analyzing accuracy measures, the advantage being that the framework uses all of the data (i.e., both successful and unsuccessful results in an experiment). Furthermore, the inverse logit function can be used to map fitted/predicted values on the log-odds scale back to the probability of interest, using the inverse of the logit function:

$$p(x) = \frac{e^{\alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_q x_q}}{1 + e^{\alpha + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_q x_q}} \qquad (3)$$

For more details on logistic regression modelling, see Hosmer et al. (2013). With the infusion of knowledge of stochastic processes, conceptual change research can stand on a new theoretical footing, connecting Markovian property or Signal Detection Theory. These theoretical perspectives depend on the emergence of a formal concept that refers to a quantity with varying values across observations but can still be considered a single entity. We now know this concept as a "random variable" (Luce, 1992, p. 659). In the context of theorizing conceptual change learning process, a 2 × 2 grid that features false positives, hits, correct rejections, and misses helps characterize the uncertain mental state when a learner meets anomalies for the first time.

A 2 × 2 Grid and its Learning Transformation

From the conception-as-intuitive-statistics perspective, the uncertainty state experienced by a learner during conceptual change can be characterized by two types of correct learning responses (hit, correct rejection) and two types of error responses (miss, false positive). Such four possible learning outcomes can be seen as a conceptual change extension of signal detection theory, tabulated below as a 2 × 2 conceptual change matrix (See Table 2). Let me return to the pendulum-or-flower puzzle in the introduction paragraph to illustrate this point. In the process of solving this puzzle, a hit means correctly identifying a pendulum as a pendulum and a flower as a flower, while a correct rejection means correctly identifying a non-pendulum object as a non-pendulum object and a non-flower object as a non-flower object. At the same time, a miss occurs when a puzzle solver does not identify a pendulum or a flower when either of them is present . In other words, the solver missed the correct answer. Similarly, a false positive comes about when she or he incorrectly identifies a gap or a non-pendulum object as a pendulum or a blank or a non-flower object as a flower. In this case, someone thought she or he had found the correct answer, but it was not correct. In this way, the process of understanding a science concept can also be characterized by the matrix covering hit, correct rejection, miss, and false positive.

Table 2

A 2 × 2 Conceptual Change Matrix

	Not Changed	**Changed**
Science Idea Presented	Miss	Hit
Science Idea Not Presented	Correct Rejection	False Positive

Such a 2 x 2 matrix form is chosen for theorizing conceptual change for the following reasons: 1) students with diverse linguistic and cultural backgrounds may possess a composite cognitive “software” structure, with information processing with both their first and second language in their respective modes. In this case, a multidimensional structure would be needed for characterizing and representing such information processing; 2) a two-dimensional structure has a natural connection with these students’ working memory-supported learning mechanisms, which features a process of perceiving anomalies while activating prior knowledge through memory retrieval; 3) the matrix form has a mathematical root and can be easily formulated as a stochastic one, thus linking linear algebra with probabilistic processes. Equation 1 is such an example.

$$I = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \qquad (1)$$

It is a rectangular array of (real or complex) numbers arranged in 2 rows by 2 columns (a 2 x 2 matrix square *I*). In linear algebra, a 2 x 2 matrix (1) is a type of transformation which maps a 2-dimensional vector to another one in the vector space. The transformation is illustrated in equation (2), in which the matrix *I* work as a transforming operator to map the vector [x, y] to [x′, y′].

$$\begin{bmatrix} x & y \end{bmatrix} \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} x' & y' \end{bmatrix} \qquad (2)$$

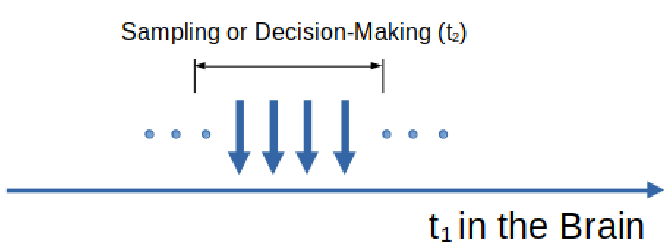
The transforming operator can be used to characterize a learner's incorporation of feedback from reading a refutation text or discussing with peers to generate new knowledge. As a mathematical construct, it does not have to be conceptualized with time. However, in theorizing learning physics concepts with prior knowledge, the notion of duration and order is necessary because every stage of human information processing, such as sampling and decision-making, takes time.

Active Learning Mechanism with Time as the Fundamental Dimension Added

Inspired by Zhou's conceptual advancement thesis (2012) and the brain's information processing, I put forward a two-dimensional conceptualization of psychological time. In particular, I assume the cognitive "software" running a mental program that features recurring sampling-and-decision-making loops in time. A unit of such a recurring process has been illustrated in Figure 3.

Figure 3

A Two-Dimensional Time-Based Framework for Conceptual Learning



Once an anomaly in a sense-making process is detected and new information is to be reintegrated, the first round of sampling and decision-making will be initiated to minimize the extent of error feedback. If the learner is still confused, a second round of sampling and decision-making will be engaged until a criterion is achieved. These sampling and decision-making events are probabilistic, which implies that each time the result of such an active information processing will be different, with only a central tendency and conceptual distribution patterns observed. As shown in this figure, there are t1 and t2 bundled together, with the former representing the temporal aspect of a learning mind capable of processing information actively. The width of t_2 is an instance of temporal Gestalt, representing the discrete, quantum aspect of human information processing. The dots on the two sides illustrate the continuity of oscillating sampling and decision-making rounds. The directions of t_1 and t_2 show an ideal orthogonal relation connecting these time elements. Together, the whole construct can be seen as one token of the two-dimensional time T. With a binomial distribution of possible conceptual change responses, a 2 × 2 learning outcomes grid, and a time-based active learning mechanism, the learner side of conceptual change learning has been characterized by the notion and language of probability. The last missing theoretical piece is a new taxonomy of concepts.

The Mathematically Defined Physics Concepts and Conceptual Change

For college or university students, the physics concepts they might meet to learn in liberal arts programs or science courses are different from those they get familiar with daily. Most of these physics concepts are defined or expressed mathematically. Take the most straightforward concept, the period of a pendulum or *force,* for example. Intuitively, time is associated with a process with a duration or a before-or-after relation, whereas force is associated with the experience of pushing or pulling an object. However, the physics identification and mathematical calculation of the period say it is a product with a coefficient

2π and a square root of a quotient (*l /g).* Similarly, a Newtonian force is expressed as another product of two terms: mass and a change in velocity ($\frac{dv}{dt}$), as expressed in the equation form below:

$$F = m \times \frac{dv}{dt}$$

In the language of mathematics, this equation tells us clearly that the force exerted on an object is directly proportional to the mass of the object and the acceleration it experiences. In introducing the rise of the mechanical view, Albert Einstein and Leopold Infeld wrote,

> When and where we observe a change in velocity, an external force, in the general sense, must be held responsible. Newton wrote in his *Principia*:
>
> An impressed force is an action exerted upon a body, in order to change its state, either of rest, or of moving uniformly forward in a right line.
>
> This force consists in the action only; and remains no longer in the body, when the action is over. For a body maintains every new state it acquires, by its *vis inertiae* only. Impressed forces are of different origins; as from percussion, from pressure, from centripetal force. (Einstein, 1966, p. 11)

The mathematical definition of force is equivalent to the verbal descriptions penned repeatedly since the mathematization of physics. In this sense, a concept can be conceptualized as a mental construct defined half-mathematically-and-half-verbally. Similarly defined physics concepts can easily be found in conceptual physics textbooks or the reviewed conceptual change studies. Minchul Kim, Youngwook Cheong, and Jinwoong Song (2018) categorized seven mathematically defined physics concepts to illustrate their ontological and epistemological functions in physics education. In this sense, a new taxonomy of physics concepts (See Table 3) is needed to differentiate their roles in influencing conceptual change processes.

Table 3

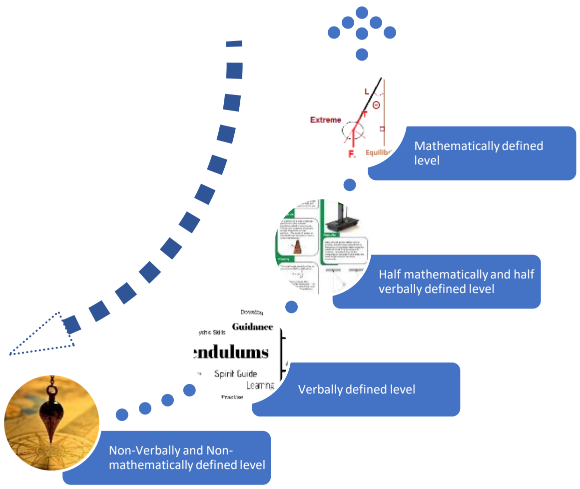
A New Taxonomy of Physics Concepts for Learning Pendulum Motion

Concept	**Type 1**	**Type 2**	**Type 3**	**Type 4**
Criteria	Mathematically Defined	Half mathematically defined and half verbally defined	Verbally defined	Non-verbally defined
Example	An imaginary number, the probability amplitude, Simple harmonic motion	Force ($F = m \times \frac{dv}{dt}$), The isochronous pendulum motion ($T_{12} = T_{21}$)	Argumentation, Ideology, Propositional perception	Visual perception, Auditory perception, Working memory system

With this taxonomy, it becomes possible to categorize and analyze the processes of conceptual change at different levels of verbal, scientific, and mathematical descriptions with greater precision. Figure 4 is an example of applying such a taxonomy to reorganize the pendulum knowledge systems.

Figure 4

Illustration of the New Taxonomy of Physics Concepts for Learning Pendulum Motion



For dramatizing the effects of using the new taxonomy, a pictorial and symbolic mixed artwork is created to foreground the conception of mathematically defined physics concepts, especially in the case of learning pendulum motion. The keywords of the new taxonomy in Figure 4 characterize a knowledge system of pendulum motion phenomena, statements, data, and a structural realist' theory about them (A. F. Chalmers, 1999; Matthews, 2015; Rowbottom, 2019; Worrall, 2007). At the bottom of the upward swing, the physical objects, natural processes, and simple events of our world occurred naturally, without the involvement of any form of symbolic processing in any language. Moving up a bit, it is human psychological aspects of observing what has happened in the world and the symbolization in English.

Next, human perception-driven statements or scientific narratives about the experience of understanding pendulum motion are located at the verbally defined level or propositional perception (Matthews, 2015). Following the level, error-term-characterized empirical observations are represented as half mathematically and half verbally defined as raw scientific data. At the top of the upward swing sits the structural realist's mathematical core: $T = 2\pi \sqrt{l/g}$ for small swing amplitudes and the real natural phenomenon hidden behind the veil of so-called "reality": an isochronous simple harmonic oscillator. Together, the upward movement of a pendulum acts as a conceptual linchpin for characterizing the scope of knowledge involved in learning pendulum motion, which spans from an event, propositional perception, and the underlying continuous mathematical identification of this phenomenon.

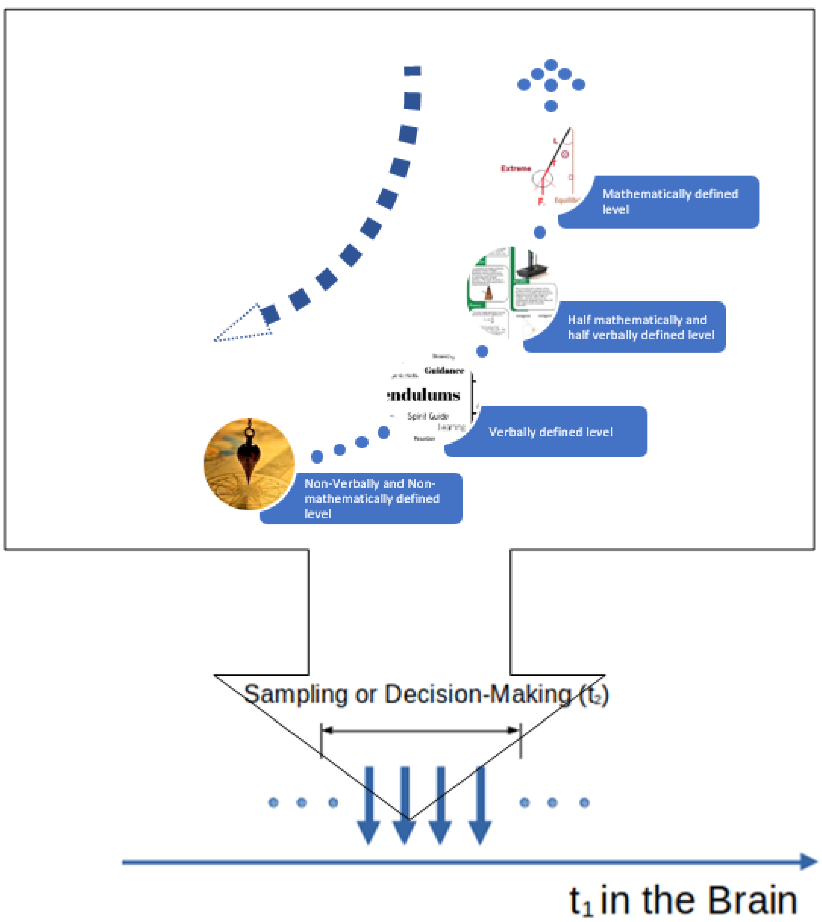
The downward swing by the side of the upward one shows a recurring information integration episode in a learner's mind. The dashed lines indicate the probabilistic nature of human information processing. Most importantly, I contend that all these episodes of information processing take time, regardless of which aspect is of interest. In this sense, students' conceptional change toward understanding the notion of a mathematical idealized simple pendulum can be tested empirically in a series of experiments. Thus, the overall effect of students' intuitive pre-instructional conceptions on their real-time responses can be measured. The last two levels of such a knowledge system must be learnt with effort over time. In light of this, an active learning mechanism is also needed to explain the conceptual change effect during such effortful science learning.

Illustration: A Theoretical Lens with a Probabilistic Frame of Reference

Balancing the qualitative and quantitative aspects of the literature and departing from the conception-as-intuitive statistics assumption, I have put forward a new theoretical framework that features a probabilistic frame of reference. The new theoretical lens consists of the following key components: (a) a binomial distribution of the intuitive and counterintuitive conceptions with an overlapping middle area represented in a learner's conceptual space, (b) a 2 × 2 learning outcomes grid, (c) a time-based active learning mechanism, and (d) a new taxonomy of concepts and conceptual change. Figure. 5 shows an enlarged part of the sampling and decision-making information processing episode, with a new taxonomy of physics concepts applied within.

Figure 5

An Enlarged Part of the Sampling and Decision-Making Information Processing Episode



Through this new theoretical lens of active learning, both qualitative and quantitative observations can be considered in the same theoretical framework, speaking the same language of probability. Also, the framework allows adopting a mixed methods approach to study conceptual change studies, thus enabling measuring students' conceptual learning in time.

Summary

This probabilistic frame of reference-based theoretical framework differs from the six major conceptual change theories (Potvin et al., 2020). In turn, they are (a) Posner's (1982) Conceptual Accommodation model, (b) Vosniadou' s (1994) Framework Revision, (c) Chi et al.'s (1994) Ontological Category Shift, (d) Hewson's (1982) Conceptual Capture or Exchange, (e) Pintrich et al.'s (1993) Warm Conceptual Change, and (f) diSessa' s (1993) P-prim Reintegration. Commonly, these models have assumed a directed timeline underlying conceptual change processes. On this one-dimensional timeline, a learner's per-instructional conceptions of scientific knowledge are transformed into a new one. In contrast, the two-dimensional time-based framework adds sampling and decision-making components to the big picture, enabling the probabilistic approach to process noisy and ambiguous binomial distribution-like students' (mis)conceptions.

CHAPTER 5 METHODOLOGICAL STRATEGIES

The existing yet unbalanced literature finds that out of the context of PER, mathematically defined concepts and conceptual change received less and less attention than they used to (Swets et al., 1961; Luce, 1992, 1996). For today's researchers, a universal narrative inquiry method seems to account for most aspects of conceptual change research. However, the new taxonomy of concepts has indicated that physics concepts cannot be understood without mathematical knowledge. Given the complexity of qualitative and quantitative data, this study adopted the convergent parallel design (Creswell, 2014) for data collection and a series of the probability-concept-based conceptual toolbox to guide data analysis. This chapter details the methodological considerations of this study. Special attention is given to the exploratory nature of my study and the complexity of data collection, analysis, and explanation through the new S-D theoretical lens and what I did to overcome the challenges.

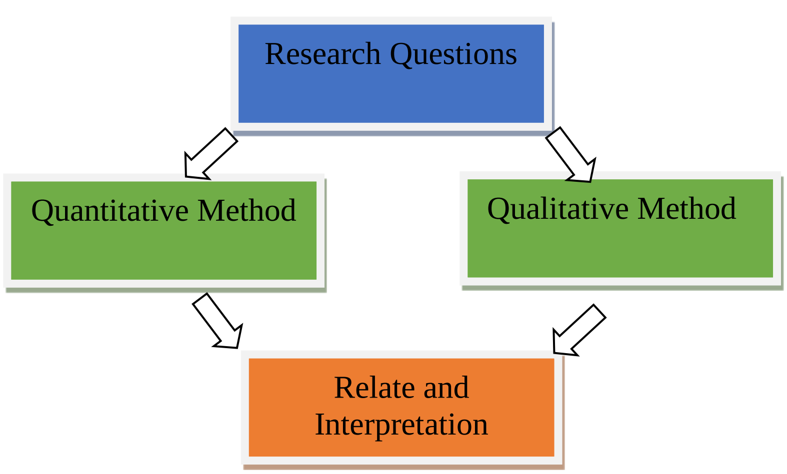
According to Creswell (2014), a convergent parallel mixed methods design combines both quantitative and qualitative data collection and analysis methods in a single study. As its name suggests, data in this design is collected concurrently and analyzed separately, then integrated during the interpretation phase to provide a more complete and comprehensive understanding of the research topic. This design allows researchers to address the breadth and depth of the research question, cross-check the findings, and validate them from both quantitative and qualitative data. This method is helpful when addressing complex research questions where a single method or approach may not fully capture the nuances of the learning phenomena being studied. Another reason to adopt a mixed-methods design was to fill the literature gap and extend the quantitative conceptual change research tradition. Moreover, quantitative data analyses would be more revealing and informative due to the millisecond timescale and error analysis.

A Mixed Methods Study Design Within Error Terms Considered

To be more specific, the first stage of this study started by collecting qualitative data on students' background information and learning experiences through a language background survey. Then, the initial exploratory qualitative results would give details regarding intra-level participants' factors. Next, their knowledge of pendulum motion was tested empirically in two experiments, which served as prototype testing and its replication but were manageable as a doctoral study. At the same time, interviews were conducted to add information about their subject experiences of the sampling and decision-making processes in the pendulum motion experimental trial. Following such a parallel qualitative and quantitative data collection, I interpreted how the quantitative data would be mapped onto the interview results and how to integrate the data to provide an overall understanding of conceptual change processes (see Figure 6).

Figure 6

A Mixed Methods Design



Strategies for Data Collection: Sampling Methods and Procedures

When this study was designed, the onset of the COVID-19 pandemic at the end of 2019 changed how participants would be recruited and how the experiments were conducted. Basically, all these procedures had to move online and be carried out over the Internet. Purposive sampling was adopted to identify and recruit participants for this study during the pandemic. According to Check and Schutt (2012), sampling aims to select individuals or groups for inclusion in a study based on specific criteria or characteristics relevant to the research question. The goal was to intentionally choose participants who could provide the most relevant and informative data to address the research questions. In order to participate in this study, the following selection criteria were adopted:

- Age: 18 years old or above.
- Vision: normal or correct to normal; no-colour blindness.
- Study permit holding bilingual international students whose mother tongue is Chinese.
- Have Internet access at home.
- Have a quiet personal space to ensure that she or he would not be disturbed during the experiment.

The Chinese Scholar and Students Association of a southeastern Canadian university was contacted to recruit the first few most informative participants who loved physics knowledge and wanted to know more about the mechanics. The snowball sampling method was adopted. Also, according to Check and Schutt (2012), the sampling features identifying a small group of participants who meet the initial selection criteria and then asking them to refer other potential participants who also meet the requirements. The international students of the same campus were thus contacted afterwards.

Addressing my research questions requires the participant's self-identification as a bilingual (the student’s self-reporting of their language skills). Basic demographic data were also gathered, followed by the experiment. There were open-ended questions inviting them to share their opinions or ideas about pendulum motion before participating in the experiment. Their inputs shed light on their selective responses during the experiments.

Actual student recruitment began after receiving the approval of research from the university’s Research Ethics Review Board. The participants were approached through email or phone. Their consent to participate and recruit other interested students for the study were also obtained through the emailing system, with their written signatures penned. The recruitment process continued till 20 participants signed up for the first experiment, 25 for the second, and 5 for the interview. There were no overlaps among the participants of the first and the second experiment. However, two second experiments’ participants agreed to share their experiences in the interviews. The sample size varied to make it manageable for a doctoral study. Each of these participants was assigned a participant number and a session number. With these numbers, they chose when to start the experiments at a convenient place of their own choice, without other specific materials involved besides their computers. Each experiment was expected to last about 45 minutes. The interviews were carried out after the end of the pandemic, so the face-to-face mode was adopted for conducting the interviews. The interview lasted about half an hour.

Strategies for Quantitative and Qualitative Data Analysis

Regarding qualitative data analyses, the purpose is to search for meaning, which may be embedded in patterns of expression or consistency across five interviewees. This way, raw interview data were analyzed to extract anchor physics concepts-related information and other unexpected clues. I reconstructed the meaningful episodes of their conceptual change learning stories with extracted evidence.

As for quantitative data analyses, both the reaction time and error rates were analyzed. As for reaction time, the analysis of variance was implemented first so that the results of this study could be compared with the documented quantitative studies reviewed in Chapter 3. Moreover, the error rates were analyzed with the logistic regression-based modelling technique. The reason for adopting a new data analysis strategy is detailed in the data analysis section of Experiment 1. Together, the results could provide a better “big” picture of students’ sampling and decision-making processes.

Ethics Concerns

Due to COVID-19, the proposed studies were moved online, with participants sitting at their homes to finish the required task. That means foreseeable risks were kept at a minimum level. As for ethics concerns, first, no deception or other types of information distortion were used in this study, and participants had a chance to know all the procedures of the experiments at the beginning of each experimental session. They could choose to quit the experiment at their will. Furthermore, participating in the experiments had no significant impact on the participants, given that their reaction times and accuracy data were the focus of this study. Their answers to the language history assessment were recorded for analysis. A possible negative effect was associated with their eyesight, which might come from reading from a computer monitor. However, a break time was scheduled to divide their screen time. Thus, the psychological and social risks associated with the research were low, with no apparent physical risks involved. Also, the risk associated with group vulnerability was low.

CHAPTER 6 EXPERIMENT 1: MATCHING THE PERIOD OF PENDULUM MOTION

The purpose of Experiment 1 was to prototype the quantitative conceptual change studies and to test-run the new online experimental platform: Pavlovia (*Pavlovia*, n.d.). The difference between this experiment and the others was its use of the Rapid Serial Presentation technique (a visual stimuli train featuring the sub-second or millisecond presentation) to highlight the temporal aspect of visual experiences. This experiment was necessary because if a consistent matching pattern in time could be found, the result of experiment 1 would serve as a baseline for subsequent experiments, including the cross-language one presenting another type of pendulum bearing the fundamental scientific laws. Moreover, the range of participants was refocused on bilingual international students with a study permit that permitted them to study in a Canadian college or university. However, the permit also set a limit to their non-academic activities outside the campus, which made the participants more comparable regarding their learning experiences in Canada.

Research Questions and Hypothesis

According to the mathematical relationship describing the pendulum period with a small release angle boundary condition ($T = 2\pi \sqrt{l/g}$), the length is the only factor that would affect the oscillation period of the pendulum motion. In contrast, other factors of the visual pendulum stimuli should not determine the time. If a learner understands the underlying reasoning, she ought to ignore the other factors when seeing them in this experiment. Experiment 1 was designed to test such a possibility while test-running the online open science platform Pavlovia with Chinese-English bilinguals. The research question asked whether visual changes in a candidate pendulum's length, bob weight, or temporal position would affect these bilinguals' matching choices. The null hypothesis of this experiment was that there would be no reaction time or accuracy differences existed among the bilinguals' responses among the experimental conditions. In contrast, the alternative hypothesis was that these participants' period-matching reaction times on these conditions would differ, reflecting their various levels of understanding of the mathematically defined pendulum motion and their sampling and decision-making processes on the fly.

Method

The first experiment was designed to measure the bilingual participants' reaction times with a within-participants design. To address the research question, I varied three visual perceptual levels of a computer-controlled display of a pendulum (length, weight, and the temporal position of a candidate pendulum). Each participant was presented with a set of such four pendulums as an experimental unit through their home computers. Upon seeing the standard and matching pendulums unit of such visual inputs, the participant indicated her responses on each experimental trial with the mouse of the visual stimuli-presenting computer. All other visual features of the stimuli were irrelevant to the purpose of this experiment. In other words, the two levels of the visual features of pendulum motion (its length and bob weight) and one level of temporal position initial release angle) were manipulated in a within-participants design, with the participants' reaction times and accuracies recorded as the dependent variables.

Participants. A power analysis was conducted to find an adequate sample size for the within-participants experimental design. A variance and an effect size were estimated, given the currently reported similar experimental results in the literature. Then the Hotelling-Lawley Trace Statistical test with a Type 1 error of .05 was calculated. The analysis result showed that a total sample size of about 35 would yield a power level of .8. Due to the onset of the COVID-

19 pandemic, however, twenty international students, aged from 18 to 55, were recruited for the first experiment (See Table. 3 for detail).

Table 4

A Summary of the Twenty Participants of Experiment 1

No	Age	Gender	Edu	Major	1st language	2nd language
01	26	F	BA	Non-Science	Chinese	English, Korean
02	22	M	BA	Physics	Chinese	English
03	32	F	Master	Non-Science	Chinese	English
04	48	F	Master	Non-Science	Chinese	English
05	24	M	BA	Physics	Chinese	English
06	30	F	Master	Non-Science	Chinese	English
07			Master	Non-Science	Chinese	English
08	36	M	Master	Non-Science	Chinese	English
09	37	F	Master	Non-Science	Chinese	English
10	18	M	High School	Mathematics	Chinese	English
11	39	F	Master	Non-Science	Chinese	No.
12	39	M	Master	Non-Science	Chinese	No.
13	45	F	Master	Non-Science	Chinese	English
14	55	F	BA	Non-Science	Chinese	English
15	44	F	PhD	Chemistry	Chinese	English
16	44	M	BA	Non-Science	Chinese	English
17	32	F	Master	Mathematics	Chinese	English
18	30	M	PhD	Biology	Cantonese	English
19	41	F	PhD	Non-Science	Chinese	English
20	19	M	BA	Non-Science	Chinese	English

They were contacted through the community of a southeastern Canadian university through contacting its Chinese Scholars and Students Association and recruitment postings.

Most of them were native Chinese speakers who could speak English, and one of them also reported Korean as one of her known foreign languages. Their participation was compensated with a $10.00 e-gift card. All the participants were naïve to the purpose of this experiment, and they reported having normal or corrected to normal vision. Table. 4 summarises the self-reports of their English language skills in reading, writing, speaking, and listening. The scale used was a 7-point one, with 1 representing “very poor” and 7 “native-like.”

Table 5

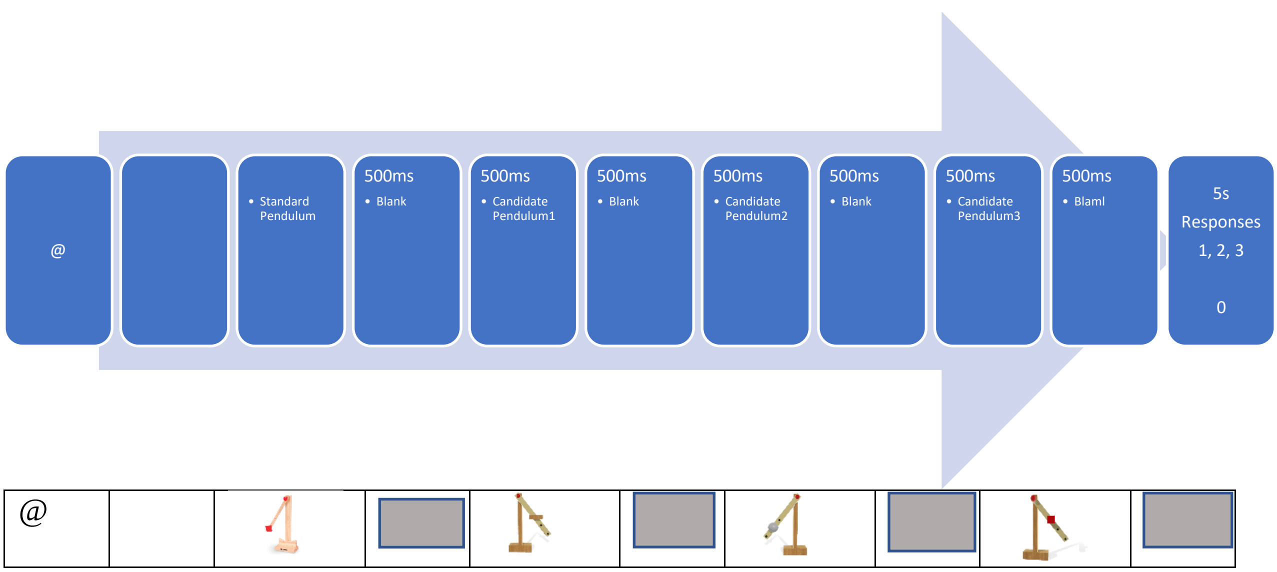
The Language Learning Background of the Twenty Participants of Experiment 1

No	Reading	Writing	Speaking	Listening
01	5	4	4	4
02	5	5	3	4
03	6	5	5	6
04	5	4	5	4
05	4	4	4	5
06	4	4	5	5
07	4	4	3	4
08	6	5	5	5
09	5.5	5.5	5.5	5.5
10	4.5	4	5	5.5
11	5.5	5	5	5.5
12	4	3	3	4
13	4.5	4.5	4.5	4.5
14	6	5	5	5
15	6	6	5	5
16	5	5	5	5
17	6	6	5	5
18	5	5	5	5
19	6.5	5.5	6.5	6.5
20	5	4	5	6

Apparatus and stimuli. As the experiment was administered by an open science online experimental site Pavlova, I did not know specific details of the apparatus the participants used. However, they were set up to present all the stimuli at the refresh rate of 60 Hz. Psychopy (Peirce, 2007), an open-source psychophysiological software package with 1 msec precision, was used to create the experiment and upload it to the online platform Pavlovia, which synchronized the stimuli generation and data collection. Students' responses were registered through the mouse of their computers.

Both a standard and the three to-be-matched pendulum stimuli were presented in a rapid serial visual presentation (RSVP) paradigm (See Figure. 7). In each RSVP trial, participants saw a coloured standard pendulum shown in the centre of the screen on a grey background. They had five seconds to closely examine this pendulum, estimating its period and other features of their interest. After clicking a CONTINUE button, a series of three candidate pendulums would be rapidly presented, with a 500ms blank duration separating them. Each of the three pendulums was equally likely to be presented at the 1st, 2nd or 3rd position. Moreover, they were equally likely to be the target pendulum or one of the two distractor pendulums. Viewing from a distance of approximately 60cm, participants were instructed to respond to a target-matching pendulum as quickly and accurately as possible.

Figure 7 *Illustration of Experimental Procedure of Experiment 1*



Design. The experiment used a within-participants design. This minimized inter-participant variability's impact across the different experimental conditions. There were three factors: (a) the length of the pendulum (long, middle, and short); (b) the weight of the pendulum bob (heavy, medium, light), and (c) the position of the target pendulum (1, 2, 3 or 0). The three factors were independently manipulated. The initial release angle was not specifically controlled in this pilot experiment.

Experimental Procedure. After signing the consent form, the participants would receive an experimental link, their unique participant numbers, and a session number. The experiment would automatically start after typing in the numbers through the link. The written instructions were presented in the middle of the screen. After reading the introduction, they would complete a language history questionnaire. The assessment was necessary because a second language skills level would affect how they processed the instructions of this experiment, thus influencing reaction times and error rates. The questionnaire covered basic demographic information, major-related questions, and language learning profiles. The information would help explain their experimental results. Next, the practice session of this experiment was presented at the same rate as that of the real one. Only their responses were not recorded. For the practice session, the item presentation rate started from 500 msec/item. No feedback was provided in practice, simulating what would occur in the real session.

Before the actual experimental session started, the participants had a chance to take a break. When they were ready again, each participant could start the real experiment by clicking the CONTINUE button on the screen. Each trial would begin with presenting a standard pendulum for viewing as long as they liked within a limit of five seconds. After they chose to click the CONTINUE button, a series of two distractor pendulums and a target one was to be presented one at a time for 500 msec at the same location in the centre of the screen. Each stream ended with a choice display showing “1”, “2”, “3”, and “0.” The participants were instructed to click on the number indicating the temporal position of the period-matching the target pendulum, with “0” indicating “no matching”, while ignoring all the other visual stimuli. Because the candidate pendulums' visual features differed from the standard pendulum, the participants could not use these visual features as clues to match the standard pendulum at the sensory or perceptual level. Instead, they would have to use their understanding of the fundamental scientific laws to choose the target correctly (also known as a hit). They were also instructed to respond as quickly and as accurately as they could by clicking on the indicating number of the temporal position of the candidate pendulum.

Data Analyses: ANOVA or Binomial Regression?

Given that the experimental condition groups' mean reaction times are the reaction times of the correct probe responses, the reaction time analyses must be limited to those probe trials in which the participants correctly identified a matching target pendulum. Moreover, the correct reaction times were constrained by a latency range between 200 and 2,000 msec. I expected most results observed in Experiment 1 to be within this range. Further analyses did not include the participants' data with over 30% error rates, which may indicate a lapse of attention in a simple selection task. The alpha level was set at .05.

Given the within-participants design, the mean reaction time data was submitted to a repeated-measure ANOVA with pendulum motion features as the within-participant factors. I expected to find the main effect of the pendulum feature, showing their understanding of the fundamental scientific laws.

Quantitative data can take many forms in education research, such as time or accuracy. In contrast to measuring learners' performance in milliseconds, it is common for education researchers to collect students' responses and mark them as right or wrong given a pre-defined theoretical position. Both teachers and researchers in education tend to draw definitive conclusions from analyzing such data, particularly after seeing a statistically significant result, yet reporting significance or not based on p-values thresholds of .05 or .01 has been contested as an acceptable good practice (Kuffner & Walker, 2019; Wasserstein & Lazar, 2016). The unsuitability is of great concern when the data modelling method may not be appropriate. Although researchers in education and psychology may be more familiar with the former, its underlying assumptions are not satisfied given the underlying nature of the error rates data. For them, adopting a logistic regression approach is more appropriate.

Results

Table 5 shows the mean correct RTs for the candidate pendulum presented at the first, the second, and the third temporal position, with 0 representing no match or a correct rejection of Experiment 1. In the same table, the error rates are also displayed. The mean RTs were the response latencies of correctly matching a candidate pendulum with the standard one. Thus, the RT analyses were limited to those probe trials in which the participants correctly identified the pendulum oscillation period. Moreover, the correct RTs were constrained by a latency range between 200 and 2,500 msec. In this experiment, 98.9% of the correct RTs were within this range. The data of five participants with over 60% error rates were not included in further analyses. The alpha level was set at .05.

Table 6

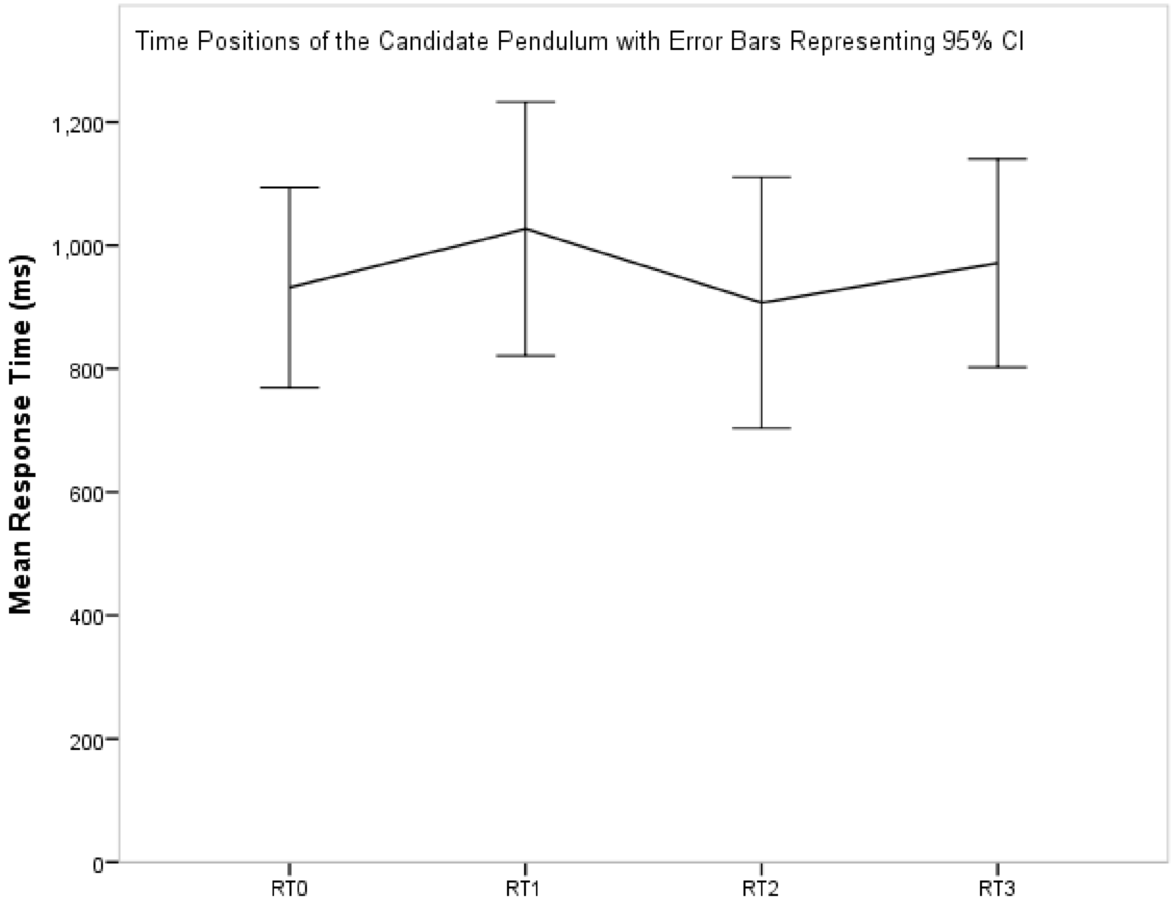
Correct Response Times and Mean error rates (% error) for the Three Time Positions of the Candidate Pendulum in Experiment 1, with No-Matching as the Zero Position.

Exp	**Participant**	**RT0(ms)**	**RT1(ms)**	**RT2(ms)**	**RT3 (ms)**	**Missing**	**Correct%**	**Error%**
1	1	823.6	2085	1684.5	1266.333	4	32.4	67.6
1	2	1759.5	1313.429	1158.857	1438.667	2	31.4	68.6
1	3	1012.059	1386	1153.909	1255.333	5	65.7	34.3
1	4	1789.222	2005.5	2016	1763.6	2	94.3	5.7
1	5	768.0625	670.2857	718.3529	815.6667	3	89.9	10.1
1	6	1131.5	2088.5	2497.667	1358.5	13	20.3	79.7
1	7	973.3889	928.0714	999.7778	1007.063	1	93	7
1	8	664.5211	708.2769	695.2031	711.7578	0	94.4	5.6
1	9	927.9111	1010.29	713.7378	912.9629	0	91.7	8.3
1	10	583.6667		855		0	13.9	86.1
1	11	1166.862	1233.119	1083.355	1366.508	4	82.4	17.6
1	12	878.5247	977.5772	762.1722	919.6922	1	97.2	2.8
1	13	929.9567	973.7313	1029.899	893.4729	0	95.8	4.2
1	14	784.2941	902.6111	784.4706	955.8824	0	95.8	4.2
1	15	1014.828	1343.771	917.91	889.02	4	85.3	14.7
1	16		1581.135	1374.62	3567.84	0	5.8	94.2
1	17	682.9363	758.1012	612.0661	703.2441	0	94.4	5.6
1	18	951.2667	1006.278	778.1111	957.1667	2	90	10
1	19	959.9	1079.929	964.4615	946.2222	3	66.7	33.3
1	20	472.5556	416.5	376.0556	469.2941	0	98.6	1.4

The mean RT data were submitted to a repeated-measure ANOVA with the temporal position of the candidate pendulum as the 4-level factor. The main effect of the temporal position was significant, F (3, 42) = 4.74, p < .01, η_p^2 = .25, indicating mean RTs differed significantly across the three time points and a non-matching level. A post hoc pairwise comparison using the Bonferroni correction showed that it took an increased response time to decide the candidate pendulum presented at the first temporal position than at the second one (1026.67 vs 907.03, $p < .05$). Also, making a no-matching decision (correct rejection) was approaching statistically significant level as compared with doing that at the first temporal position (931.75 vs 1026.67, $p = .08$). No other pairwise comparisons had reached the statistically significant level. Therefore, I can conclude that the results of the repeated ANOVA have indicated a significant time effect for matching the pendulum oscillation period as measured in time by RTs.

Figure 8

Reaction Times as a Function of the Time Positions of the Candidate Pendulum



In addition to the time position of a candidate pendulum, similar quantitative data analyzing procedures were also implemented to analyze the effects of the other two independent variables: the length of the pendulum d and the bob's weight. Table 6 shows the mean correct RTs for the candidate pendulum presented with the longest, medium, and shortest length in Experiment 1. The mean RTs were the response latencies of correctly matching a candidate pendulum with the standard one, given the length of the pendulum. The data screening considerations were the same as the analysis of RTs for the temporal positions. The alpha level was also set at .05.

Table 7

Correct Response Times for the Three Pendulum Length Levels in Experiment 1.

Exp	Participant	Longest_Time (ms)	Medium_Time (ms)	Shortest_Time (ms)
1	1	1387	2085	1198.45
1	2	1158.86	1412.56	1438.67
1	3	1120.41	1260.87	1110.83
1	4	1921	1962.5	1793.43
1	5	742	708.05	781.75
1	6	2333.86	2088.5	1209.67
1	7	989.96	983.15	963.68
1	8	720.78	685.72	678.57
1	9	750.01	949.69	963.46
1	10		597.5	556
1	11	1088.95	1231.13	1337.99
1	12	796.99	938.29	925.11
1	13	1013.14	933.67	921.31
1	14	785.7	858.35	928.39
1	15	912.03	1205.88	992.09
1	16		1581.14	
1	17	626.55	706.26	735.58
1	18	803	1046.52	902.06
1	19	1008.88	1044	906.08
1	20	427.96	421.92	450.13

The mean RT data were submitted to a repeated-measure ANOVA with the length of the candidate pendulum as the 3-level factor. The main effect of the length was significant, F (2, 28) = 4.33, $p < .05$, $\eta_p^2 = .24$, indicating the mean RTs differed significantly across the three length levels. A post hoc pairwise comparison using the Bonferroni correction showed that it took an increased response time to make a decision about the candidate pendulum with the medium-length rod than that of the longest one (995.73 vs 913.82, p < .05). No other pairwise comparisons had reached the statistically significant level. Therefore, I can conclude that the repeated ANOVA results have indicated a significant length effect for matching the pendulum oscillation period as measured in time by RTs.

Figure 9

Reaction Times as a Function of the Pendulum Length Levels

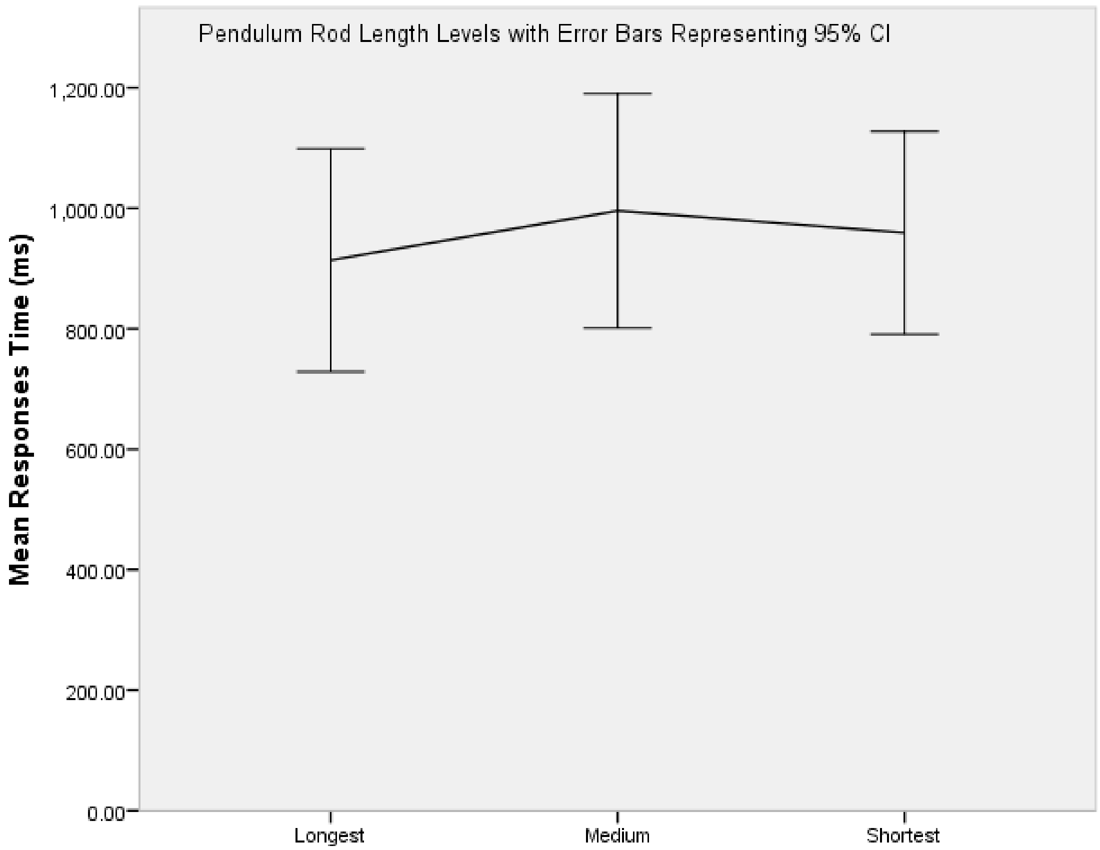


Table 7 shows the mean correct RTs for the candidate pendulum presented with the heavy, medium, and light bob in Experiment 1. The mean RTs were the response latencies of correctly matching a candidate pendulum with the standard one, given the weight of the pendulum bob. The data screening considerations were the same as the analysis of RTs for the temporal positions. The alpha level was also set at .05.

Table 8

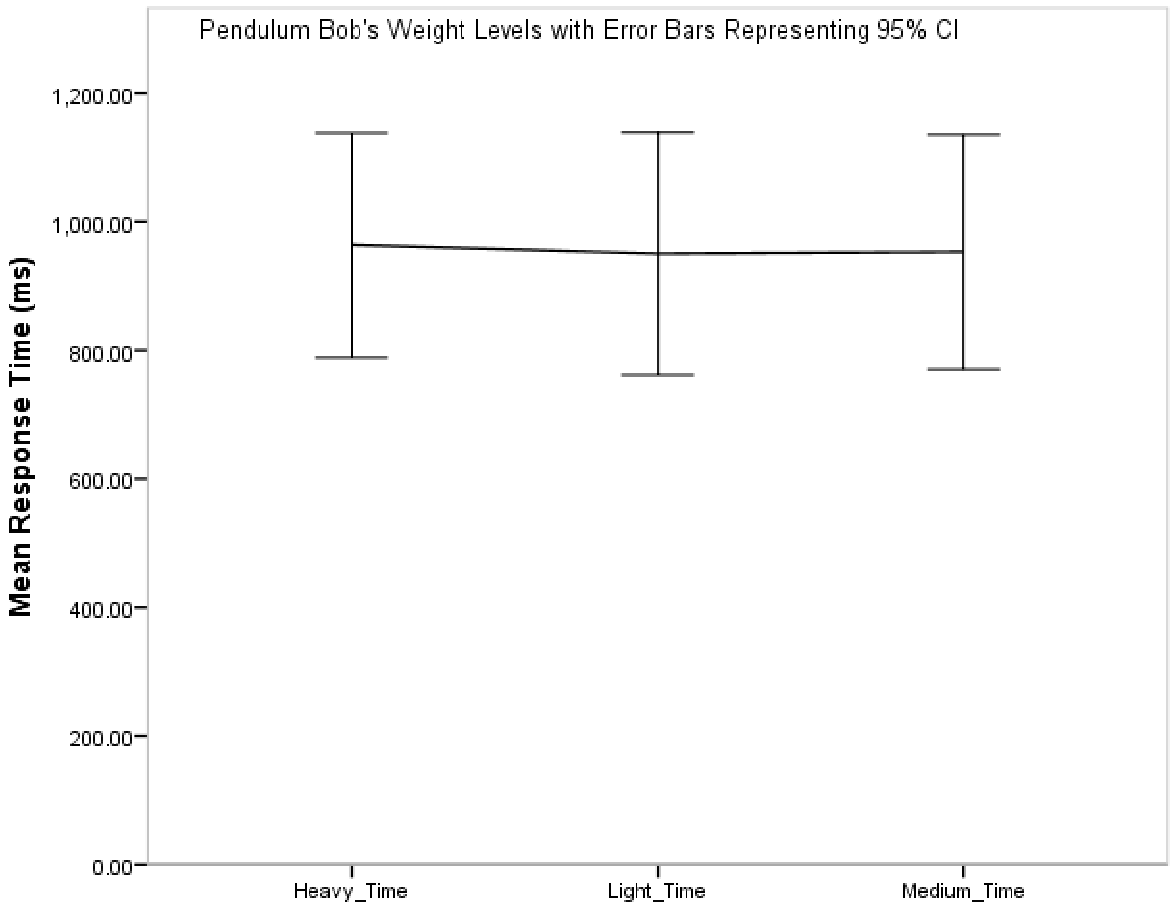
Correct Response Times for the Three Pendulum Bob Weight Levels in Experiment 1.

Exp	Participant	Heavy_Time(ms)	Light_Time(ms)	Medium_Time(ms)
1	1	1249.71	1493.57	1323.63
1	2	952.56	1660	1544
1	3	1212.93	1117.84	1188.18
1	4	1820.12	1968.91	1897.19
1	5	748.19	700.68	789.11
1	6	1398.25	2664.25	1973.25
1	7	1015.22	931.71	981.42
1	8	730.92	673.55	669.97
1	9	917.41	844.75	873.48
1	10	564.33	593.33	
1	11	1254.9	1208.41	1190
1	12	893.19	899.59	858.76
1	13	939.02	975.78	961.27
1	14	850.59	877.23	845.05
1	15	895.7	1082.84	1122.33
1	16			1581.14
1	17	702.17	694.4	664.57
1	18	1036.3	807.76	898.74
1	19	1030.79	1005.71	931.31
1	20	408.52	468.48	425.95

The mean RT data were also submitted to a repeated-measure ANOVA with the bob weight of the candidate pendulum as the 3-level factor. The main effect of the bob weight was insignificant, $F(2, 28) = .22$, $p > .05$, indicating the mean RTs were not different across the three bob weight levels.

Figure 10

Reaction Times as a Function of the Pendulum Bob's Weight Levels



In brief, two statistically significant results have been identified in Experiment 1 following the repeated ANOVA methods. First, the time position of a candidate pendulum did affect the participants' decision-making, increasing their matching response times when the first candidate pendulum had to be selected from the other alternatives. Second, the oscillation period of the mid-length pendulum took more time to be judged as the same as that of the standard pendulum. All other experimental manipulations of Experiment 1 did not have the same response time-extending effects, such as the weight of pendulum bobs.

As introduced in the data analysis strategy section, the ANOVA methods may not be suitable for analyzing error rates. The logistic regression-based modelling of accuracy data was adopted for the error rates observed in this experiment. The R commands in Appendix A showed the model-building procedure and the results of model comparisons.

Table 9

A Summary of Three Binomial Logistic Models and the Statistical Indexes

Dependent Variable	Predictor	*df*	*b*	*t*	*p*	sr^2	95% CI
corrAns	position	1,057	0	-0.3	0.767	0	[0.00, 0.00]
	length	**1,057**	**0.04**	**3.12**	**0.002**	**0.01**	**[0.00, 0.02]**
	id	1,057	0	1.79	0.073	0	[0.00, 0.01]
	position	1,056	0	-0.31	0.757	0	[0.00, 0.00]
	length	**1,056**	**0.04**	**3.13**	**0.002**	**0.01**	**[0.00, 0.02]**
	weight	1,056	0	-0.26	0.797	0	[0.00, 0.00]
	id	1,056	0	1.79	0.073	0	[0.00, 0.01]
	position	1,055	0	-0.33	0.744	0	[0.00, 0.00]
	length	**1,055**	**0.04**	**3.15**	**0.002**	**0.01**	**[0.00, 0.02]**
	weight	1,055	0	-0.29	0.773	0	[0.00, 0.00]
	reading	**1,055**	**-0.07**	**-6.13**	**< .001**	**0.03**	**[0.01, 0.06]**
	id	**1,055**	**0.01**	**3.41**	**0.001**	**0.01**	**[0.00, 0.02]**

Table 10

Results of Model Comparison Results of the Three Embedded Mixed Effects Models of the Experiment 1 Data

Model	AIC	BIC	LogLik	Deviance	χ2	*df*	*pr* (> χ2)
cc1	687.49	707.35	-339.74	679.49			
cc2	689.55	714.39	-339.78	679.55	0.0000	1	1.00000
cc3	687.06	716.86	-337.53	675.06	4.4952	1	0.03399 *

* $p < .05$

Note. *cc1* means a model built with R command "corrAns ~ position + length + (1 | id)" whereas *cc2* "corrAns ~ position + length + weight + (1 | id)" and *cc3* "corrAns ~ position + length + weight + reading + (1 | id)."

The analyses of the error rates have added some informative data to the response time results. Commonly, the length of the pendulum has been singled out as a significant predictor of making a correct decision about its oscillation period. However, the time position of a candidate pendulum has not been shown as another significant one. Most importantly, when the participants' reading levels were added to the logistic regression equation, it was identified as a significant predictor of making a correct decision in a pendulum period-matching trial. All other predictors have not been shown by both the response time and error rate analyses as significant.

Discussion

Several aspects of the observed patterns of the data are worth noting. First, there was a temporal position effect in identifying and matching the period of a pendulum. As this is one of the first studies using a series of candidate pendulums to measure students' responses, the outcome needs particular consideration. The time difference between making a decision about the first and the second candidate pendulum reveals a serial effect of human memory retrieval mechanisms. It indicates that regaining the pendulum matching information from the represented distribution of the first candidate pendulum was more challenging than another overlapping distribution of the second time position. The structure of the candidate pendulum representation distributions determined the signature of such a time course in matching the period of the pendulum motion.

Second, the evidence suggests that deciding on a correct rejection was faster than hitting the first candidate pendulum, though only a marginally significant time difference had been observed in Experiment 1. This result was likely caused by the extent of memory loading involved in making such a negative response. In other words, less memory loading was needed for "saying-no" to a series of candidate pendulums. With the no-matching visual stimulus sampled after seeing a trial, it seems that the participants did not need to keep activated any knowledge distributions activated for completing the task, thus only using less time to click the "no-matching" selection. Given the marginally significant result, there are other possibilities worth further exploration.

Besides the role of the time position of a candidate pendulum in determining the time course of matching a pendulum period, the third observed aspect was a significant effect of the length of the pendulum in this experiment. The time difference observed between deciding the candidate pendulum with the medium-length one, and that of the longest one seems to reveal a differentiating effect of human memory retrieval mechanisms. It indicates that regaining the pendulum matching information from the represented distribution of a mid-length pendulum was more challenging than from another overlapping distribution of the longest one. Again, the structure of the candidate pendulum representation distributions determined the characteristic feature of such a time course in matching the period of the pendulum motion. No similar results have been observed for varying the weight of pendulum bobs over the experimental conditions. The results indicate that the participants paid attention to the key determining factor of the pendulum, showing the effect of students' knowledge of the pendulum motion.

Fourth, it is worth noting that no interaction effects were observed between the time position and the length of the pendulum. This result indicates that the candidate pendulums presented in another time position may be processed similarly. This is likely because only one candidate pendulum needed to be selected out of the series once the distributed information of the first two-time positions had been processed. There was no further need to process the last temporal position in an experimental trial, or it would be easier to process the last.

At last, the analyses of the error rates have confirmed the response time results. By a binomial logistic regression-based technique, the length of the pendulum has also been singled out as a significant predictor of making a decision correctly. However, the time position of a candidate pendulum has not been shown as another significant predictor. Interestingly, when the participants' reading levels were added to the logistic regression equation, it was identified as a significant predictor of correctly matching the pendulum period. All other predictors have not been shown by both the response time and error rate analyses as significant.

CHAPTER 7 EXPERIMENT 2: INTERLANGUAGE FEEDBACK AS TRAINING

In the first experiment, the response time of deciding about a pendulum period-matching task was the main focal point of concern. The analyses have shown comparable reaction time data documented in the literature. However, only the length of the pendulum had been identified as a significant predictor of the participants' choices over a series of candidate pendulums. Moreover, the pendulum was only one type of various pendulums, and it was still unclear whether a similar result could be observed with other variants of a pendulum. Most importantly, the visual stimuli of Experiment 1 were the computer-generated pictures of pendulums, which may not elicit the same responses as the participants saw a real one. Given these concerns, the next experiment was designed with another famous type of pendulum: a string pendulum with and without two isochronous cheekpieces to control the initial release angle of a pendulum bob.

Research Question and Hypothesis

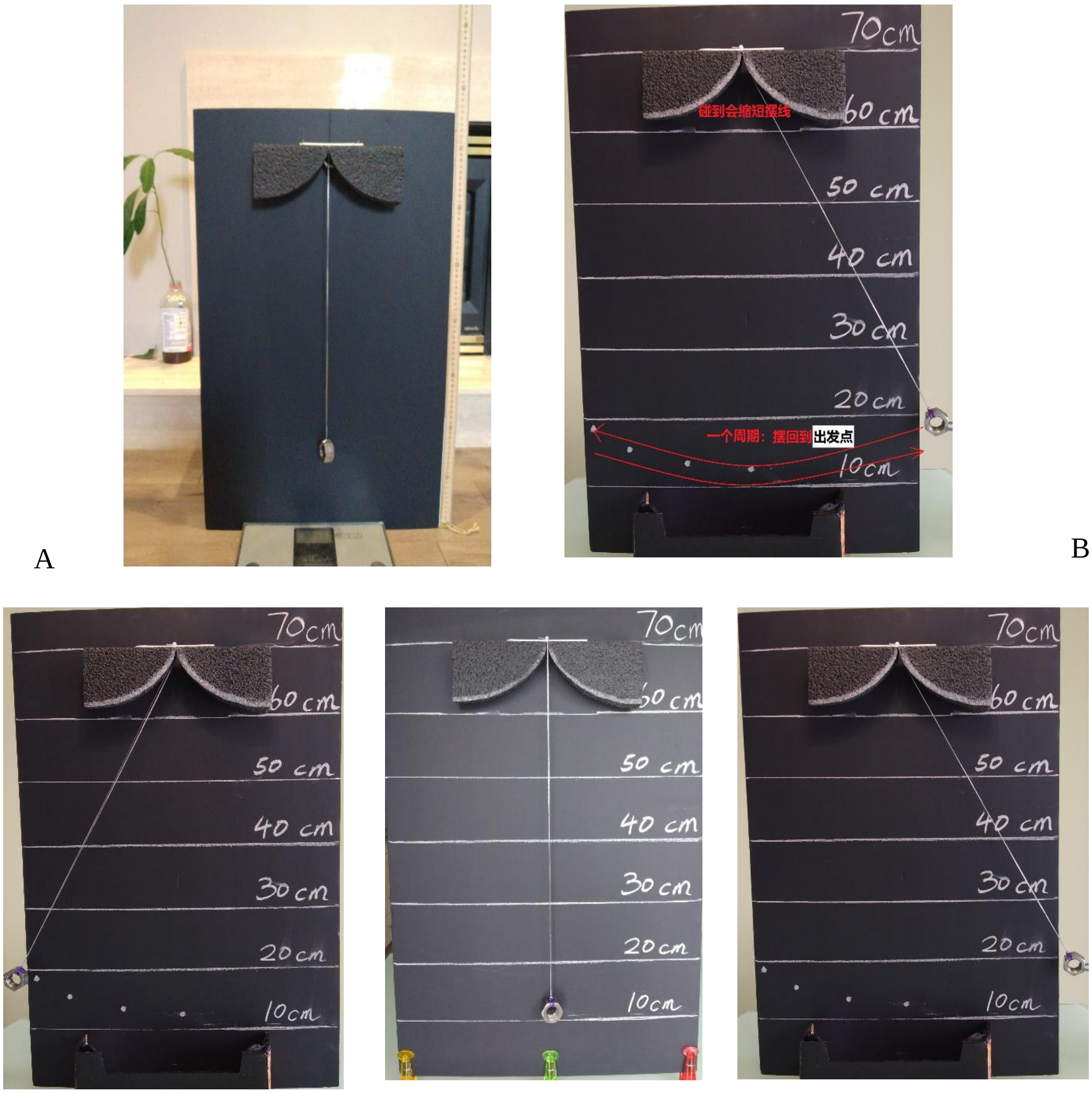
Experiment 2 addressed the following research question: Will their second language-based feedback, which was to be presented as feedback on their correct and incorrect responses, change the patterns of their reaction times? The null hypothesis was that there would be no differences after receiving the cross-language feedback. In contrast, the alternative was that such instruction-like cross-language feedback would induce significant reaction time differences.

Method

The second experiment was designed to measure the participants' reaction times with a within-participant experimental design. To address the research questions, I constructed a string pendulum with two string-shortening inverted cheeks fixed at the top of the pendulum (See Figure. 10) .

Figure 11

The String Pendulum for Experiment 2



In the illustration, the pendulum in cell A shows its basic feature: the string and the inverted cheeks. Cell B has added some notations, showing its dimension, the definition of an oscillation period, and the function of the two cheeks. Cells C to D depict three possible positions of the swinging pendulum. Also, three independent variables were varied in Experiment 2 (the time position of a candidate pendulum, cheeks presented or not, and initial release angle). A set of visual stimuli were presented to each participant through their home computers. Some different design features were presented in this experiment but not in Experiment 1. First, an annotated pendulum, as shown in Cell B, was presented for teaching and clarifying the key concept of an oscillation period of a pendulum. Secondly, there was feedback on each trial. Upon a correct period-matching, the word “Correct!” would appear on the screen to show the result. Otherwise, the online feedback changed to “Sorry, got it wrong, 注意摆幅和摆线长度.” (“Pay Attention to the Amplitude of the Swing and the Length of the String.” My English translation, but not shown to the participants) These added features have modified Experiment 2 and made it feel like a real learning episode, with specific inputs and online feedback.

Upon seeing these visual inputs, they indicated their responses on each experimental trial. All other visual features of the stimuli were irrelevant to the purpose of this experiment. In other words, the three levels of pendulum motion (cheeks presented or not, initial release angle, and time positions of a candidate pendulum) were manipulated in a within-participants rapid serial visual presentation experiment, with the participants’ reaction times and accuracies as the dependent variables.

Participants. Another sample of students was recruited for this experiment and received a 10-dollar e-gift card for their participation. Due to the onset of the COVID-19 pandemic, however, twenty-three international students aged 18 to 49 were recruited. All are naïve to the experiment's purpose and reported to have normal or corrected to normal vision.

Table 11

A Summary of the Twenty-Three Participants of Experiment 2

No.	Age	Gender	Edu Level	Major	1st language	2nd language
01	22	M	BA	Other	Chinese	Yes
02	23	F	Master	Other	Chinese	English
03	40	F	Master	Other	Chinese	English
04	45	M	Master	Other	Chinese	English
05	28	M	PhD	Other	Chinese	English
06	30	F	Master	Other	Chinese	English
07	35	M	BA	Biology	Chinese	English
08	18	F	BA	Mathematics	Chinese	English
09	24	F	BA	Biology	Chinese	English
10	46	F	BA	Other	Chinese	English
11	33	F	Master	Other	Chinese	English
12	49	M	PhD	Other	Chinese	English
13	27	F	Master	Other	Chinese	English
14	28	F	Master	Other	Chinese	English
15	41	F	PhD	Other	Chinese	English
16	40	F	PhD	Other	Chinese	English
17	30	M	Master	Other	Chinese	English
18	30	F	Master	Other	Chinese	English
19	40	F	BA	Other	Chinese	English
20	45	F	PhD	Other	Chinese	English
21	31	F	BA	Other	Chinese	English
22	31	M	BA	Other	Chinese	English
23	42	M	BA	Other	Chinese	English, French

Similarly, the Chinese Scholars and Students Association of the university located in southeastern Canada helped me to recruit the participants for this experiment. The participants were native Chinese speakers who learned English as their second language. None of them had prior knowledge of this experiment's objective, and they confirmed having regular or corrected eyesight.

Table 12

The Language Learning Background of the Twenty-Three Participants of Experiment 2

No.	Reading	Writing	Speaking	Listening
01	5	5	5	5
02	7	7	7	7
03	4	4	4	5
04	5	3	5	5
05	3	4	3	3
06	6	6	4	6
07	7	5	7	6
08	5	4	4	4
09	6	5	6	5
10	5	4.5	4	5
11	6	4	4	4
12	5	5	5	5
13	4	5	4.5	4.5
14	6	4	4	3
15	6.5	6.5	6.5	6.5
16	6.5	6.5	6.5	6.5
17	6.5	5.5	5	6
18	5	5	5	5
19	5	2	4	5
20	5	5	6	6
21	5	5	5	5
22	4	4	4	4
23	4	4	4	4

Apparatus and stimuli. The same online platform was used for presenting stimuli and collecting responses, except for the added features. I did not know specific details of the apparatus the participants used. However, they were set up to present all the stimuli at the refresh rate of 60 Hz. Psychopy (Peirce, 2007), an open-source psychophysiological software package with 1 msec precision, was used to create the experiment and upload it to the online platform Pavlovia, which synchronized the stimuli generation and data collection. Students' responses were registered through the mouse of their computers.

Both a standard and the three to-be-matched pendulum stimuli were presented in an RSVP paradigm. In each RSVP trial, participants saw a standard string pendulum shown in the centre of the screen on a black background. They had five seconds to closely examine this pendulum, estimating its period and other features of their interest. After clicking a CONTINUE button, a series of three candidate pendulums would be rapidly presented, with a 500ms blank duration separating them. Each of the three pendulums was equally likely to be presented at the 1st, 2nd, or 3rd position. Moreover, they were equally likely to be the target pendulum or one of the two distractor pendulums. Viewing from a distance of approximately 60cm, they were instructed to respond to a target-matching pendulum as quickly and accurately as possible.

Design. The experiment used a within-participants design. This was to minimize the impact of inter-participant variability across the different experimental conditions. There were three factors: (a) the inverted cheeks (present, not present), (b) the initial release angle of the pendulum bob (big, small), and (c) the time position of the target pendulum (1, 2, 3 or 0). The three factors were independently manipulated. All other factors were not explicitly controlled in this experiment.

Experimental Procedure. After signing the consent form, the participants would receive an experimental link, a unique participant number, and a session number. The experiment would automatically start after typing in the numbers through the link. The written instructions were presented in the middle of the screen. After reading the introduction, they would complete a language history questionnaire. The assessment was necessary because a second language skills level would affect how they processed feedback information, thus influencing reaction times and error rates. The questionnaire covered basic demographic information, major-related questions, and language learning profiles. The information would help explain their experimental results. Next, the practice session of this experiment was presented at the same rate as that of the real one. Only their responses were not recorded. For the practice session, the item presentation rate started from 500 msec/item. No feedback was provided in practice, simulating what would occur in the real session.

Before the actual experimental session started, the participants had a chance to take a break. When they were ready again, each participant could start the real experiment by clicking the CONTINUE button on the screen. They would see the annotated pendulum first. Next, each trial would begin with presenting a standard pendulum for viewing as long as they liked. After they chose to click the CONTINUE button, a series of two distractor pendulums and a target one was to be presented one at a time for 500 msec at the same location in the centre of the screen. Each stream ended with a choice display showing “1”, “2”, “3”, and “0.” The participants were instructed to click on the number indicating the temporal position of the period-matching the target pendulum while ignoring all the other visual stimuli. Because the visual features differed for the standard pendulum and the matching target one, the participants could not use these visual features as clues to match the standard pendulum. Instead, they would have to use their understanding of the fundamental scientific laws to choose the target correctly (a hit). They were also instructed to respond as quickly and accurately as possible by clicking on the number of temporal positions of the candidate pendulums, with “0” indicating "no matching." Upon a correct matching of the oscillation period of pendulum motion, the word “Correct!” would appear on the screen to show the result. Otherwise, the online feedback changed to “Sorry, got it wrong, 注意摆幅和摆线长度.” (“Pay Attention to the Amplitude of the Swing and the Length of the String,” My English translation, but not shown to the participants)

Data Analyses

To make the results comparable with those of Experiment 1 and the experimental research tradition, the data analyses of this experiment were also split into two parts: the response time and error rates. The first part used the repeated ANOVA procedures and the analysis of error rates through the binomial logistic regression techniques. Again, the focus was on whether the time position of a candidate pendulum would affect the participants’ decision-making and whether the presence of the inverted cheeks and the amplitude would influence their responses. Moreover, the correct RTs were constrained by a latency range between 200 msec and 2,500 msec. In this experiment, 98.9% of the correct RTs were within this range. The data of one participant with the highest missing rate were not included in further analyses. The alpha level was set at .05.

Results

Table.12 shows the mean correct RTs and the error rates of the probe trials, respectively. The data were treated in the same way as in Experiment 1. One participant’s data were excluded from further analyses because of missing over 20 trials. Once again, only correct RTs ranging from 200 msec to 2,000 msec were analyzed. Over 96% of the RTs were within this range. Also, the mean correct RTs are for the candidate pendulum presented at the first, second, and third temporal positions, with 0 representing no match or a correct rejection of Experiment 2. In the same table, the error rates are also displayed. The mean RT data were submitted to a repeated-measure ANOVA with the temporal position of the candidate pendulum as the 4-level factor. However, their differences did not reach a significant level after submitting the data to a repeated ANOVA procedure.

Table 13

Correct Response Times and Mean error rates (% error) for the Three Time Positions of the Candidate Pendulum in Experiment 2, with No-Matching as the Zero Position.

Exp	Participant	RT0	RT1	RT2	RT3	Missing	Correct%	Error%
2	1		1045	757	726	3	33.3	66.7
2	2	1300	1435	833	1038	1	38.9	61.1
2	3	1352	1668	1795	1780	1	61.1	38.9
2	4	1308	1042	1416	1649	3	45.8	54.2
2	5		1246	1128	1158	0	30.6	69.4
2	6		2092	2261	1288	1	23.6	76.4
2	7	836	848	933	1022	1	51.4	48.6
2	8		1532	1383	1204	0	41.7	58.3
2	9	2246	1931	1786	2132	1	40.3	59.7
2	10			1405	1589	1	23.6	76.4
2	11	1018	1500		1580	0	51.4	48.6
2	12		1817	1809	1542	1	34.7	65.3
2	13		857	1147	1470	0	34.7	65.3
2	14			1436	1475	3	16.7	83.3
2	15		1898	1624	1623	1	31.9	68.1
2	16	1986	1940	1574	2409	5	38.9	61.1
2	17		1302	1222	1205	1	40.3	59.7
2	18		1207	810	1865	5	23.6	76.4
2	19		1478	1460	1446		33.3	66.7
2	20		1750	1500	1273		41.7	58.3
2	21	1667	1606	3105	1624	3	38.9	61.1
2	22	879	1706	994	1453		37.5	62.5
2	23	2302	1867			21	22.2	77.8

In addition to the time position of a candidate pendulum, similar quantitative data analyzing procedures were also implemented for examining the effects of the other two independent variables: the presence of the inverted cheeks and the amplitude of the initial release angle of the pendulum bob. Once again, the mean RT data were submitted to a repeated-measure ANOVA with the presence of a pair of inverted cheeks of the candidate pendulum as the 2-level factor. However, their differences also did not reach a significant level.

Next, the mean RT data of the amplitude of the initial release angle of the pendulum bob were submitted to a repeated-measure ANOVA with the big and small amplitude as the 2-level factor. The main effect of the amplitude of the initial release angle was significant, $F\ (1, 21) = 5.02$, $p < .05$, $\eta_p^2 = .19$, indicating the mean RTs differed significantly across the two amplitudes of the initial release angles. A post hoc pairwise comparison using the Bonferroni correction showed that it took an increased response time to make a decision about the oscillation period of the candidate pendulum with a large initial release angle than that of the small one (1557.27ms vs 1384.47ms, $p < .05$). Therefore, I can conclude that the result for the repeated ANOVA has indicated that a significant amplitude effect of the initial release angle for matching the pendulum oscillation period as measured in time by RTs in Experiment 2.

Table 14

The Repeated ANOVA Results of the Correct Response Times for the Two Initial Release Angle Levels in Experiment 2.

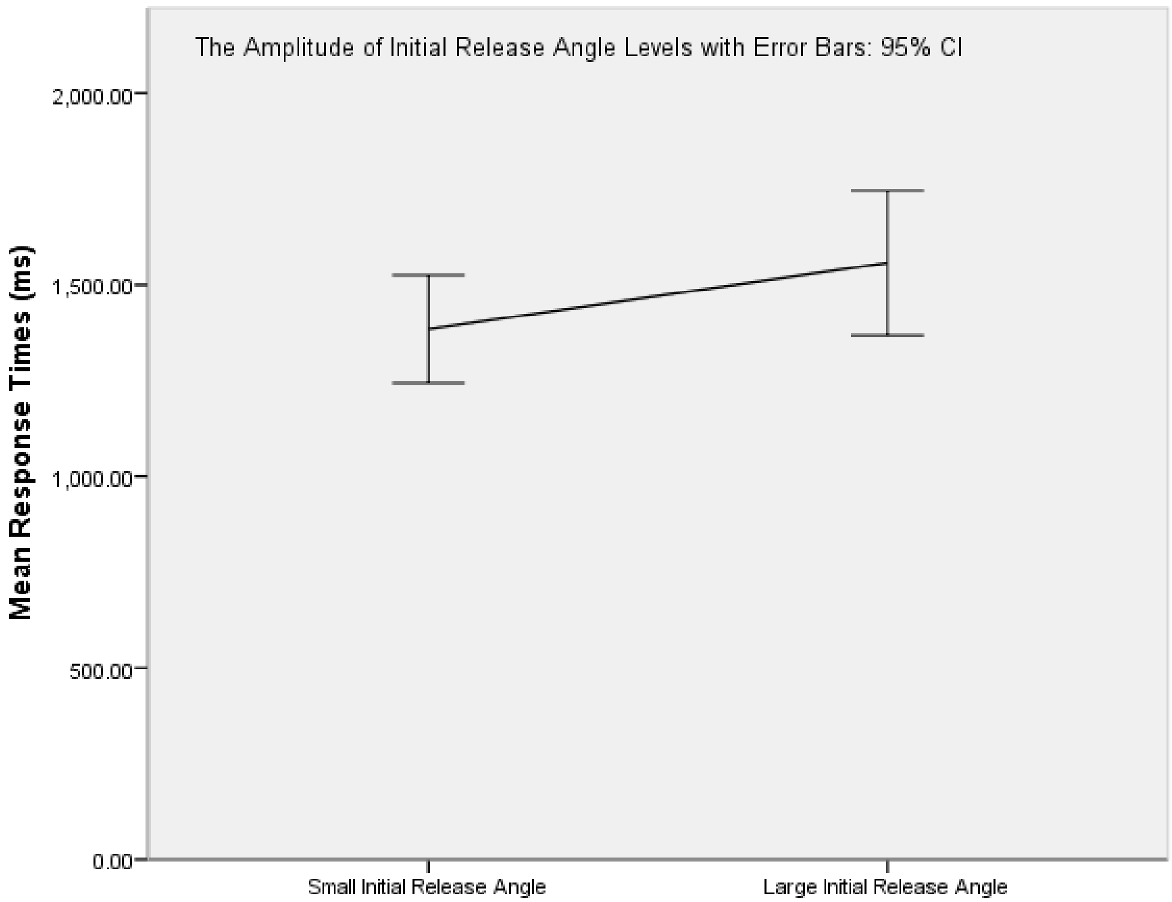
Measure: MEASURE_1

Source		Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Initial_Release_Angle	Sphericity Assumed	328444.765	1	328444.765	5.019	.036	.193
	Greenhouse-Geisser	328444.765	1.000	328444.765	5.019	.036	.193
	Huynh-Feldt	328444.765	1.000	328444.765	5.019	.036	.193
	Lower-bound	328444.765	1.000	328444.765	5.019	.036	.193
Error(Initial_Release_Angle)	Sphericity Assumed	1374257.708	21	65440.843			
	Greenhouse-Geisser	1374257.708	21.000	65440.843			
	Huynh-Feldt	1374257.708	21.000	65440.843			
	Lower-bound	1374257.708	21.000	65440.843			

The contrast between the mean RTs were also illustrated in Figure 11.

Figure 12

Reaction times as a function of initial release angle



In summary, only one statistically significant result has been identified in Experiment 2 following the repeated ANOVA methods: the amplitude of the initial release angle of a pendulum bob. That is to say, the participants were drawn to the boundary condition of the string pendulum used in this experiment. However, the non-significant results seem to suggest that they ignored the added inverted cheeks for controlling the influences of a large initial release angle. All other experimental manipulations of Experiment 2 did not have the same response time-extending effects, such as the time position of a candidate pendulum.

Following the data analysis strategy adopted for Experiment 1, the ANOVA methods were not used for analyzing error rates. For the error rates observed in Experiment 2, the logistic regression-based modelling of accuracy data was implemented again. As indicated by the data analyses of Experiment 1, the participants' self-reported reading levels were also added as a predictor in this analysis. The R commands can also be found in Appendix B, which shows the model building procedure.

Table 15

A Summary of Three Binomial Logistic Models and the Statistical Indexes

Dependent Variable	Predictor	*df*	*b*	*t*	*p*	sr^2	95% CI
	position	**1,580**	**0.08**	**7.30**	**< .001**	**.03**	**[0.02, 0.05]**
	cheeks	**1,580**	**-0.06**	**-2.40**	**.017**	**.00**	**[0.00, 0.01]**
	Id	1,580	-0.00	-1.95	.051	.00	[0.00, 0.01]
	position	**1,579**	**0.06**	**5.57**	**< .001**	**.02**	**[0.01, 0.03]**
	cheeks	**1,579**	**-0.07**	**-2.66**	**.008**	**.00**	**[0.00, 0.01]**
	angle	**1,579**	**-0.18**	**-6.00**	**< .001**	**.02**	**[0.01, 0.04]**
corrAns	Id	1,579	-0.00	-1.57	.116	.00	[0.00, 0.01]
	position	**1,578**	**0.06**	**5.55**	**< .001**	**.02**	**[0.01, 0.03]**
	cheeks	**1,578**	**-0.07**	**-2.63**	**.009**	**.00**	**[0.00, 0.01]**
	angle	**1,578**	**-0.18**	**-6.01**	**< .001**	**.02**	**[0.01, 0.04]**
	reading	1,578	0.01	0.44	.663	.00	[0.00, 0.00]
	Id	1,578	-0.00	-1.55	.122	.00	[0.00, 0.01]

Table 16

Results of Model Comparison Results of the Three Embedded Mixed Effects Models of the Experiment 2 Data

Model	AIC	BIC	LogLik	Deviance	χ2	*df*	*pr* (> χ2)
cc1	2016.9	2038.4	-1004.47	2008.9			
cc2	1991.0	2017.8	-990.48	1981.0	27.97	1	1.231e-07 ***
cc3	1992.9	2025.1	-990.46	1980.9	0.0526	1	0.8186

*** $p < .001$

Note. *cc1* means a model built with R command "corrAns ~ position + cheeks + (1 | id)" whereas *cc2* "corrAns ~ position + cheeks + angle + (1 | id)" and *cc3* "corrAns ~ position + cheeks + angle + reading + (1 | id)."

The analyses of the error rates of Experiment 2 have added some information to the response time results. When the predictors were added together in a binomial regression model, the time position of a candidate pendulum, the presence of the cheeks, and the amplitude of the initial release angle were shown to be significant in predicting the error rates of matching the oscillation period of a string pendulum. In contrast, the reading levels of the participants were not. Most importantly, the temporal position and the amplitude of the initial release angle were both identified as highly significant predictors of the participants' error rates.

Discussion

In Experiment 2, the participants responded to a string pendulum with two string length-changing cheeks installed at the top of the pendulum. Also, the amplitude of the initial release angles of the string pendulum varied across the experimental conditions. In contrast to the pendulum used in Experiment 1, the weight of the pendulum bob was not varied, whereas the length of the pendulum string was only modified when being released from a large initial angle. Therefore, there were no visual similarities exited between the pendulums used in the two experiments. However, the same mathematical definition of pendulum period $T= 2\pi\sqrt{l/g}$ determined the oscillating behaviour of pendulum motion, especially when being released from a relatively small initial angle. When the small angle boundary condition was not met, the period of pendulum motion would no longer be isochronous. A new element of pendulum knowledge must be added to interpret the changing behaviour of such a pendulum. Also, this experiment added an instructional episode and response feedback to the candidate pendulum series in an experimental trial. The instructions were meant to illustrate the definition of the period of pendulum motion in a graphical manner. The feedback was added to change the students' overlapping knowledge distributions over pendulum motion.

Given the similarities and differences between these two experiments, several aspects of the observed patterns of the results are worth discussing. First, there was no temporal position effect in identifying and matching the period of a string pendulum regardless of the presence of the cheeks. One possibility of such a negative result seems to suggest that an increased difficulty of Experiment 2 has removed the time differences. Alternatively, the same result indicates that the participants have not observed the experimental manipulations about the cheeks, the amplitude, and the initial release angle. The third possibility is that the missing data in Experiment 2 was higher than in the first experiment. All these possibilities await further exploration.

Interestingly, the effect of the amplitude of the initial release angles of the pendulum was significant in this experiment. In particular, the participants took an increased response time to decide about the oscillation period of the candidate pendulum with a large initial release angle than that of the small one (1557.27ms vs 1384.47ms, $p < .05$). Such a time difference was in expectation because the length-changing cheeks were added to modify the oscillating behaviour of the string pendulum. When the boundary condition of a small initial release angle was not met, more time would be needed to decide its oscillating behaviour. The 172.8 millisecond time difference was the first evidence supporting the interpretation that two different knowledge distributions might be underlying such a decision. All other experimental manipulations have not produced similar significant results.

However, the analyses of the error rates with the binomial logistic regression model have shown some interesting results. When all the predictors were added together into a binomial regression model, the time position of a candidate pendulum, the presence of the cheeks, and the amplitude of the initial release angle were shown to be significant in predicting the error rates of matching the oscillation period of a string pendulum. In contrast, the reading levels of the participants were not, thus confirming the resulting pattern identified in the reaction time analyses. Most importantly, the initial release angle's time position and amplitude were identified as highly significant predictors of the participants' error rates. The time position was shown to be a significant predictor because the underlying statistical distribution used in this analysis was different. The fact that the reading level was not identified as significant indicates that cheeks-related knowledge may not appear as often as that of a simple single pendulum oscillating within small angles.

Summary of Quantitative Results

Over two experiments, some interesting results have been observed. The time position of a candidate pendulum has been shown to be a significant factor in determining the participants' response times when deciding about the pendulum's oscillation period. In Experiment 1, the time position effect can be seen from the reaction time analyses. In contrast, in the second experiment, it was shown as a significant predictor using the binomial logistic regression modelling techniques. Together, they support the conclusion that the rapid serial visual presentation has revealed the dynamic aspect of making a period-matching decision. The first time position demands more cognitive resources, such as more rounds of sampling over its represented knowledge distribution.

When the length of a rod pendulum was manipulated in Experiment 1, it was shown to affect the matching decision significantly, indicating the flexibility of the participants' sampling and decision-making of processing the mid-length pendulums. When the amplitude of the initial release angle was manipulated in Experiment 2, it also resulted in a significant effect, suggesting the existence of the boundary condition of the sampling pendulum motion. When the small initial release angle was not met, the participants took a little longer to make a correct decision or hit a target.

When the participants' reading levels were included in the regression analyses, their predicting ability was mediated by the difficulty of the pendulum matching task. When the task was easy, and the participants may have read a lot about the pendulums of small initial release angles, the reading level was shown to be a significant predictor. In contrast, the reading material of the pendulums of large initial release angles was limited. The same predictor was shown to be not significant.

At last, the evidence observed in Experiment 1 has shown the potential of using the 2 × 2 learning outcomes matrix in characterizing the pendulum period-matching task. In particular, making a decision of a correct rejection was faster than hitting on a candidate pendulum, though only a marginally significant time difference has been observed. This result was likely caused by the nature of making a negative response. Given the marginally significant result, however, this result is worth further exploration.

CHAPTER 8 VERBAL EVIDENCE: A FOCUS ON STUDENTS' LIVED SAMPLING AND DECISION-MAKING

To answer the research questions about international students' sampling and decision-making during conceptual learning, I focus on data that reflect students' verbally symbolized processes in this chapter. The findings of this linguistic qualitative type are based on my analysis of five student interviews and a micro-analysis of their changing frame of references when discussing pendulum motion. The presentation of international students' sampling and decision-making perspectives are enriched with their interpretations of the mathematical equation: $T = 2\pi\sqrt{l/g}$ in their first language: Mandarin Chinese. I present the most meaningful episodes of five international student participants in the following. Among them, Jiasi Liu, Zijie Shen, and Fang Wang are Canadian Study Permit holders studying at either the local university or the college. Xun Shen and Nina Cyw have graduated from local educational institutions. However, they both claimed that they once were the Permit holders. Among these five interviewees, two volunteered to participate in Experiment 2. The interviews provided a rare opportunity to study their experiences of the experiment and address their concerns. In this chapter, the episode excerpts were translated from Mandarin.

Description of the Pendulum Motion Interview Guide

When conducting the interviews, the interviewer first used a physical pendulum constructed from a white string with several silver-coloured gaskets (a metallic mechanical seal for preventing fluid or gas leakage) to demonstrate what a pendulum was and the basic terms that would be used in the interviews. Then, the interview focused on eliciting participants' understanding of pendulum motion. All the interviews took place in a quiet and private space and followed the same general structure to maintain consistency in data collection. The interviews were recorded and transcribed first in Mandarin, and then, the transcriptions were translated into English for analysis. The English translation of the interview questions can be found in Appendix C and D. The qualitative results are organized according to their understanding of possible factors in determining the period of a simple physical pendulum and its mathematical identification.

Theme 0: Interviewees' Intuitive Ideas about Pendulum

The first interviewee arrived early and described herself as a graduate student of the master's program offered locally. When asked about her daily pendulum experiences, she mentioned watches, the tower bell in a temple, and the hypnotist's pendants that swung back and forth to mesmerize a client. This was the only case in the interviews where an interviewee connected pendulum motion with the popular spiritual aspect of culture: hypnotization. To the same question of intuitive ideas of the pendulum, the second interviewee answered differently. To him, clocks, rope swings, and the rocking "pirate ship in a playground were such examples.

The third interviewee was a graduate holding a master's degree in civil engineering. Also, he participated in Experiment 2 and was intensely interested in the interview. I also used the same interview guide for this interview. The same types of interview questions were asked again to examine his understanding of pendulum motion. Besides rope swings and grandpa clocks, the interviewee did not give other daily examples showing pendulum motion.

To the fourth interviewee, she brought up pendulum clocks, a lever, and the rope swing. The last interviewee also mentioned the old-style Grandpa clocks and rope swings. In addition, she talked about a Ping Pong training device with one end buried in the ground and the other oscillating back and forth. The training apparatus resembles an inverted pendulum.

Commonly, they spoke of watches and clocks and rope swings in the playground, which relate to their daily experiences tightly. In addition to the common living experiences with the time measuring and entertaining objects, they also showed their unique contact with other devices, such as a hypnotist's pedant, the "pirate" ship, and the Ping Pong training device. After exploring their intuitive ideas about pendulum motion, the interviewer moved on to asking questions about their physics domain-specific knowledge.

Theme 1: On Pendulum's Linear Restoring Force

One of the most salient features regarding the motion of a pendulum is its restoring force, which acts on a pendulum bob to bring it back to its original position. In the case of the gasket-based pendulum, the force brings the gasket back to its equilibrium position (the position where it hangs straight down). In algebraic terms, it is linear, suggesting that it is proportional to the displacement of the bob from its equilibrium position. That is to say, the further the bob is from its equilibrium position, the stronger the restoring force that pulls it back toward that position. This mathematized restoring force is what gives a pendulum its characteristic motion. As the silver-coloured gasket swings back and forth, the restoring force causes it to accelerate toward its equilibrium position at the bottom of each swing. This acceleration causes it to speed up until it reaches the bottom of the swing and then starts to slow down as the restoring force pulls it back up the other side. This back-and-forth motion of the pendulum (一个往复过程) is what makes the pendulum motion such an interesting and useful mechanical device. In the interviews, I first asked the five interviewees about the linear restoring force when they saw the oscillating pendulum.

When asked about what kinds of forces were involved in a pendulum motion while seeing the movement of our string gasket pendulum, Interviewee #1 mentioned air resistance and gravity. However, it seemed to her that the weight and gravity were the same. In her verbal expression,

> Interviewee #1: If there are any, maybe it's the gravitational force from the center of the Earth, but gravity and weight are the same thing, right? Probably not.
>
> Interviewer: What do you think?
>
> Interviewee #1: It's possible that it has its own weight.
>
> Interviewer: Hmm.
>
> Interviewee #1: Then, it gradually stops, it won't just keep floating down like that. As it swings down, its weight also pulls it, so it gradually returns to the vertical position. That's what I think.

For the first interviewee, she knew the force as a word and could use it to answer the questions about pendulum motion. However, her reasoning was still fragmented, without a coherent way to explain pendulum motion as illustrated in Section 8.1. The same question was answered differently by the second interviewee.

Interviewee #2' s responses were unexpected from a force-acceleration conceptual framework. He went directly to a new concept of energy and its vocabulary. To him, the process of converting potential energy to kinetic energy was the reason to move the pendulum. When prompted to describe the single pendulum from a force-acceleration perspective rather than an energy one, he added the component of gravity and the force of air resistance, and he confirmed that there were no other forces. During his analysis of the role of gravity in driving the string pendulum's motion, he realized the significance of the force of suspension on the string. With this realization, he was able to analyze the pendulum motion more thoroughly by considering the constitutive component of the forces and the concept of the combined force.

Also, this was the only case in the interviews where an interviewee showed his knowledge of geometry-based reasoning, a typical thinking style characterizing the understanding of pendulum motion in the pre-calculus era. However, his reasoning was fragmented, alternating between his physics intuitions and mathematical reasoning.

Addressing the same question about the linear restoring force, interviewee #3 mentioned idealization-based reasoning and gravity. When his answer was repeated with a rising tone, however, he added air friction. To him, the tension force of the pendulum string was ignored for simplicity. In his own words,

> Interviewee #3: We have to simplify this environment as much as possible. Yes, ah, simplify as much as possible. We discard all the factors that we think have little impact. When we pick it out, it's just a point, and it's just a point. There's no such thing as friction, and it can be done. And the line may not even be elastic, and it may all be there. Discarding these factors, we just think of it as a purely physical environment, and it's just related to gravity.

Interviewee # 4 also only mentioned gravity as the restoring force of the gasket-based pendulum while observing its suspension in the middle of the air. When asked about the possible factors that determined the period of pendulum motion, the last interviewee # 5 listed air resistance, gravity, height, and a push. Responding to the interview question of what kinds of forces might bring the pendulum back to its balance position. She answered in a self-reflective manner: "Resistance. What kind of resistance? Air resistance. Air resistance gradually slows down its speed. Along with gravity, it brings it back to this balance position." Given her response, it seemed she had the vague notion of a combined force consisting of air resistance and gravity. Somehow, the tension force originating from the suspension point was also ignored.

In sum, all the interviewees expressed clearly that they thought gravity acts as the restoring force to bring back the pendulum bob to its balance position. Most of them also mentioned air resistance. One of them, interviewee # 3 added the idealization-based reasoning for his explanation. Two of them showed their conceptualization tendency of using a vector combination in explaining the restoring force of the pendulum. Commonly, the tension force of the string was ignored, which acted significantly in determining the combined restoring force, tangential to the curve that the gasket bob traced in the air.

Theme 2: On the Weight of the Gasket-Based Bob in Affecting the Swing Period

A second salient feature regarding any pendulum is the weight of a pendulum bob. One common intuitive idea students often have about pendulum motion is that the weight affects its period. However, this is not true; it is a false positive identification. In this sense, the weight of the pendulum bob, co-determined by its mass and the force of gravity, does not affect the swing period because the acceleration of a pendulum due to gravity is constant regardless of the weight of the bob. In other words, two pendulum bobs of different weights but the same length tend to have the same swing period due to the same gravitational acceleration. However, to an intuitive mind, heavy objects like rocks are often seen to fall faster than lighter ones such as leaves. If this were the case, the weight of the pendulum bob would affect the amount of time that the gasket-based pendulum takes to complete one full swing, from the initial release point to the lowest point and then back again. In the interviews, I also asked the interviewees' conceptions about the false positive identification of the weight of the gasket-based bob in affecting the swing period.

When asked about the possible effects that the weight of the pendulum bob would have on the entire swing period of the pendulum, Interviewee #1 stated that it would shorten the period by saying, “The period would become shorter, and the swing would be faster.” Upon further questioning about the underlying reasons, she added that “when it has weight, as it swings down, gravity pulls it down faster. So, the heavier it is, the faster it swings down.” After being prompted to consider the swinging-up aspect of the pendulum motion, she hesitated in an uncertain status. In her own words,

> Interviewee #1:
>
> I think it might cancel out, but...
>
> Interviewer 2:
>
> Do you think it will cancel out completely?
>
> Interviewee #1:
>
> Because the weight should be greater than the force used to swing up to this point, I don't know what it's called specifically, so there might still be a difference.
>
> Interviewer 2:
>
> So there's still a difference.
>
> Interviewee #1:
>
> Yes, so the period might be shorter.

Here, the dialogue shows the interviewee’s confirmation bias in only attending to the downward side of the pendulum motion while ignoring the other aspect, and she can not reach a conclusion on the spot, thus jumping to a false positive one.

Similarly, interviewee #2 first said that changing the weight of the pendulum bob would shorten the swing period. However, he seemed to confuse the concept of the duration of pendulum motion and the unit duration of a single full swing. After clarifying the concept of the period, he changed his mind and said the period would remain the same. However, his conception was that a larger surface area of a weight-added bob would create more air resistance. The speeding-up effect of the added weight would be cancelled out. When encouraged to think in an idealized air resistance-free environment, he returned to his initial conception of the weight's shortening effect on the entire swing period of the pendulum.

The third interviewee's responses differed from those of the first two. When asked about the effect of the gaskets' weight on the period of pendulum motion, interviewee #3 gave a negative result while pointing out the string length as the only factor. He remarked:

Interviewee #3: No, it doesn't.

Interviewer: Why?

Interviewee #3: It only has to do with the length of the string.

…

Interviewee #3: The reason is that, um. Uh, if we're just talking about frequency or period or frequency, it can't be said that this material in this place, we can just treat it as a point mass and it's fine.

Clearly, he has avoided the false positive identification of the weight as a factor in affecting the period of a pendulum by relying on his mathematical model-based reasoning. Meanwhile, he repeated that only the length would be a factor in this regard.

Interviewee #4 also gave a negative answer, thus correctly rejecting the consideration of weight as a factor in determining the period of the pendulum. However, her conception of the independence of the weight in affecting the period of the pendulum was that gravity is the same for both light and heavy objects. Even when being prompted that more mass meant more weight, she insisted on her first response but could not explain it further.

In the last interview, I asked interviewee #5 about the relationship between the weight of the pendulum bob and its swing period. She mentioned her learning experience from Experiment 2. To quote her:

Interviewee #5: "It doesn't have an effect."

Interviewer: "Why do you say that?"

Interviewee #5: "Didn't we just learn about it last time?"

Interviewer: "If you think about it yourself..."

Interviewee #5: "I think it will have an effect."

…

Interviewee #5: "If we judge it based on common sense, I think that something heavy will move faster, and something light will move slower."

…

Interviewee #5: "If I go by my previous understanding, then I think it will have an effect. Yes, but after receiving scientific education last time, I know that the correct answer is that it doesn't have an effect."

She clearly kept a hybrid conceptual space where both pre-instructional and the scientific reasoning of pendulum motion co-existed. With her memories of the experience with the experiment, she can answer the interview question correctly without understanding the pendulum motion itself.

In summary, three of the five interviewees can correctly reject considering the weight as an influential factor in determining the period of a pendulum. However, their conceptions differed, with one relying on his mathematical reasoning, the second insisting on the result, and the third referring back to her learning experiences. The other two interviewees provided a false positive result, saying that it would shorten the period of a pendulum.

Theme 3: On the Length of the String in Affecting the Swing Period

The third salient feature of any pendulum is the length of its string and its effect on determining the period of the pendulum. As a correct identification, one of the commonly accepted answers to the question about the length lies in another concept: the harmonic oscillator swinging with conservative energy. It characterizes the pattern of the motion of a system with a restoring force that is proportional to the displacement from equilibrium. An idealized pendulum is a classic example of a harmonic oscillator, where the restoring force is provided by gravity while constrained by the tension of the suspending string. When a pendulum is displaced from its equilibrium position, the combined force of gravity and the tension force pulls it back towards its original position, causing it to oscillate back and forth periodically.

According to the mathematical language of physics, the period of a pendulum is directly proportional to the square root of its length: $T = 2\pi\sqrt{l/g}$. In other words, the equation implies that as the length of the string increases, the period of the pendulum also increases. It tells numeracy-and-equation-sensitive students that the period of a pendulum depends only on its length and acceleration due to gravity and not on its mass, amplitude, or initial release angle, which is known as the isochronous nature of a pendulum. However, this idealization scenario is achievable only under some boundary conditions, such as a small initial release angle and no air resistance.

When asked about the effect of length in determining the period of pendulum motion, Interviewee #1 mentioned the difficulty by saying that “it was hard to think about the scenario.” After receiving encouragement and reminding her that this was not an exam, she said:

> Interviewee #1: I haven't thought about this problem before. If I think about it, it's a bit long. I don't think there should be any change.
>
> Interviewer: You don't think there's any change?
>
> Interviewee #1: Right, because no matter how long the length is, the angle is the same. Well, as long as the angle is the same, I feel that it has nothing to do with the length.
>
> Interviewer: Hmm, why is that?
>
> Interviewee #1: Because if you look at it this way, this is the line, and then when it swings up at this angle, it will always form this kind of triangle.
>
> Interviewer: Right.
>
> Interviewee #1: And if the length becomes shorter, the angle of the triangle is still the same. It's just that the length of the triangle that forms the triangle has changed. I feel that if the angle is the same, the result should be the same, and the period should not change.

She even used geometric reasoning to support her decision-making on the effect of the string length on the pendulum motion. However, her conception was not aligned with the scientific understanding of the mechanism of the pendulum motion.

Similarly, the second interviewee did not correctly identify the length effect in affecting the period of the pendulum by saying, “I don't think it would affect it.” When encouraged to explain the underlying reasons, he added that “Um, let me think. I can't really explain it. It's just the way it is…It’s just a feeling.” In contrast, the interviewee #3 insisted on correctly identifying the length as the only factor in determining the swing period of the pendulum by repeating, “It only has to do with the length of the string” and “The law is derived from formulas.”

On asking the same question, the interviewee #4 had a correct identification of the length effect on the period of the pendulum by saying, “Um, I think if it's shorter, the period should be shorter too.” However, she can not give a theoretical explanation. Her explanation was based on one aspect of her living experiences. In her conception, she noted, "Um...well, I feel like it might be..because of... hair. Like if you tie your hair in a braid, a longer braid would swing longer and take more time, while a shorter braid would swing shorter and take less time. It's just a feeling I have.” The last interviewee also gave a correct answer to the question. However, her conception was that a larger swinging amplitude would be for a longer string and a smaller one for a shorter one. Following such reasoning, she concluded that a longer string meant a longer period.

In sum, three interviewees correctly identified the length of the string pendulum as the determining factor of the period of the gasket-based pendulum. Their conceptions varied from the mathematical formula and living experiences to alternative explanations. The other two insisted that the length would not have an effect in affecting the pendulum’s period.

Theme 4: On the Initial Release Angle in Affecting the Swing Period

The last salient feature regarding the motion of a pendulum is its initial release angle, the angle between the vertical and the string when the pendulum is first released from rest and another source of students’ misconceptions. Intuitively, students tend to believe that the initial release angle affects the pendulum's period. However, this is not true. In this sense, the initial release angle is often falsely identified as the effective period-determining factor. One of the possible reasons that might lead to such a false identification is its visual effect. The initial release angle of a pendulum creates a larger amplitude of its swing; thus, the larger the swing, the longer the period. Despite the visual effect, it does not affect its period. As discussed in earlier chapters, the period of a pendulum is determined by the length of the string. In other words, a string pendulum with a longer string will have a longer period than one with a shorter string, regardless of its initial release angle. The false identification of the initial release angle, in this case, may be induced by confusing the friction's amplitude-damping effects with the isochronous feature of the pendulum.

When asked about the possible effects that an initial release angle has on the period of the pendulum, Interviewee #1 expressed a notion of the boundary condition of initial release angles of a pendulum by saying that "Yes, maybe, for example, between 15 and 30 degrees, there won't be much difference because the angle hasn't changed too much. But maybe beyond a certain value, such as after 30 degrees, then its period will be shorter than 15 degrees." To explain such a change, she attributed it to gravity. In her own words, "Because, because gravity becomes stronger. Although the path becomes longer, its period may be shorter, similar to 30 degrees, with the same period. That's how I feel, and maybe there's a specific angle situation where even though the angle increases, its period is the same as when the angle is small." Even when the interviewee repeated her conception of gravity by saying, "Because, if it's too large, it means the gravity is too strong." She replied, "Yes, that's right."

To answer the same question, Interviewee #2 used an arc-based conception for responding to the interviewer's enquiry. In other words, to him, a smaller initial release angle would lead to a shorter arc for the bob to cover as the new path. He explained that "If it's short because its motion along the arc is small. Yes, the period is a little shorter." Thus, he has reached a false identification of the effect of an initial release angle in determining the period of the pendulum notion by appealing to the length of the arc traced by the pendulum bob.

As expected, the third interviewee responded to the same question by saying “no.” a correct rejection of identifying the initial release angle as a relevant and effective factor in this case. In his words, he commented, “Actually, release angle and release angle don’t affect it.” He has maintained a consistent response due to his reliance on the mathematical identification of the period of pendulum motion.

To the same question of the initial release angle, Interview #4 falsely identified it as an effective factor by saying, “Um, I think the size (amplitude) does affect it. Like if you release it from a higher point, it should take longer to swing.” When asked about her reasoning, she added that “Um, I just feel like if you release it from really close, it might swing a few times and stop. But if it's longer, it should take longer to swing.” It seems she has confused the total swing time of a pendulum with the unit swing period in her mind. Even after hearing the interviewer’s repetition of her reasoning, she confirmed, “Yeah, that's what I think.” Clearly, she did not correctly reject the initial release angle as an irrelevant factor in this case.

For the last interviewee, she again switched back to her hybrid conceptual space to give a correct answer following the prior learning experience. She said, “So, that means that the time only has to do with the length of the arm (string). It has nothing to do with the weight of the object hanging below it, and it has nothing to do with the angle at which I release the pendulum.” When asked about her reasoning process, she mentioned her learning experience in participating in Experiment 2 by saying, “Um, I had never seen it before you explained it to me.” Thus, she can correctly reject the initial release angle as a relevant factor without understanding the underlying damping-related process in this case.

In brief, two of the five interviewees have correctly rejected the initial release angle as an effective factor in determining the period of pendulum motion, whereas the other two have falsely identified this factor. Among them, one has provided a boundary-condition-based mixed response to the interview question. Their conceptions have ranged from mathematical reasoning, the arc-based conception, to the learning experience-based explanation.

Theme 5: On the Swing Period's Mathematical Identity: T= 2 π $\sqrt{l/g}$

In contrast to the above salient features of pendulum motion, which can be seen, identifying the period of pendulum motion with a mathematical equation is not so obvious. The equation $T = 2\pi\sqrt{l/g}$ plays a crucial role in the study of pendulum motion and serves as a fundamental mathematical identification for students to achieve for refining their understanding of oscillatory pendulum motion. However, they may find it challenging to grasp this equation's significance due to its mathematical equation's construct. In the interviews, I asked the five interviewees about their understanding of the equation. When showing the equation to the interviewee #1, she responded by commenting on her previous responses during the interview, "Right, it seems like what I was thinking is opposite, haha! And conversely, if its gravitational acceleration is smaller, then its period will be larger." Upon seeing the equation, she immediately checked whether her previous responses were correct. After a brief reflection, she found out the connection of these factors in determining the period by commenting:

Interviewee #1: No, actually...out of all these variables, it only depends on the length.

Interviewer: So you got that just by looking at this formula?

Interviewee #1: Really?

Interviewer: If you were given this formula, what would you think?

Interviewee #1: I think it's like this, because they are all constants and only L is changing.

Interviewer : OK. That's right, you just need to see this formula, and you think the conclusion is only related to L.

Interviewee #1: Yeah, it's interesting that it's only related to length! Haha!

At the end of the first interview, the interviewee added,

Interviewee #1: "I think physics is pretty amazing. Only this one, for the others with different weights and angles, I thought the period would become shorter, but it's not the case. It turns out that only this one affects it. I think physics is pretty amazing."

Interviewer: Yes, it's quite amazing.

These final comments displayed the first interviewee's amazement at the potential instructional value of physics knowledge. Given what she said in the interview, I tentatively conclude that as a non-science major student, her experience with the scientific reasoning of using the mathematical equation has been enriching and rewarding, even in this most straightforward case of discussing pendulum motion.

Similarly, the interviewer showed the second interviewee the same mathematical equation of the period of pendulum motion and asked for his comments. Without the interviewer finishing the question, the interviewee interrupted and declared, "That is, actually only related to length. Everything else is fixed quantities." After such a realization, the interviewee quickly solved the problem of adjusting the position of the pendulum bob to shorten the period of the pendulum motion of a slowing-down grandfather clock.

As a science-stream student in high school, Interviewee #2's knowledge structure is evidently aligned with the textbook-presented physics knowledge: an energy-based perspective and a force-acceleration-based one. The evidence I observed showed he could switch between these knowledge systems. However, his responses were fragmented when being explored with verbal interview questions. Only after seeing the mathematical equation, he immediately jumped to the correct conclusion without too much reasoning using either the energy-based or the force-acceleration-based conceptual framework and the languages. Compared with the responses of the first interviewee, it can be said that the structure of his physics knowledge was more sophisticated, especially in using mathematical reasoning and the vector-based force language to explain the pendulum motion. However, the knowledge did not guarantee the correct responses, especially when checked from the first responses.

As introduced earlier, the third interviewee was the only one who emphasized the mathematical aspect of the equation. Moreover, he described the mathematical relationship in detail. In this aspect, he remarked: “Hmm, gravitational acceleration and pi are constant values. This period only has to do with that L. Hmm…and it’s a uh…exponential function relationship, right? A half-power exponential function relationship.”

Given his responses, I can tell that the third interviewee was the only one who relied on mathematical thinking, which contrasts the way of reasoning employed by the first two interviewees. The sampling and decision-making differences can be attributed to his training in civil engineering and background knowledge in science. He was the only interviewee who continued the mathematical and scientific training after graduating high school. Such a background has enabled his reliance on the mathematical equation and the idealization process to explain pendulum motion.

In this aspect, the fourth interviewee was different. She declared that she was not good at physics from the beginning of the interview. Upon seeing the mathematical equation, she noted, “Oh, physics is my weakest subject. Yes, um, I probably haven't seen it before.” After being encouraged to express her impression of the equation, she continued:

> Interviewee #4: Um, my first impression would be 2 π . Pi is the circumference of a circle. Um, I only remember that r squared is...I probably only remember things about math. Um, I'm not sure what 2 π means exactly, like two circumferences...but the square root part feels a bit complicated. But L represents length.
>
> Interviewer: Yes, it represents the length of the line.
>
> Interviewee #4: Length divided by weight.
>
> Interviewer: No, that's gravitational acceleration.
>
> Interviewee #4: Gravitational acceleration! Length divided by gravitational acceleration; I really don't understand that.

Her responses sharply contrast the third interviewee's answers to the same interview question. Whereas the latter relied on the symbolic forms of this equation, the fourth interviewee had to figure out the exact meaning of each symbol, let alone the mathematical relationship among these symbols. However, when asked about the implementation question about adjusting the position of the pendulum of a slowing-down pendulum, her answer was the same as the engineering student had given out. Given the evidence, sometimes a correct response to a probing question may not always equal a proper understanding of the same phenomenon.

At the end of the last interview, I asked the fifth interviewee the same question about the mathematical equation. She commented on having forgotten it. I also asked her whether she wanted to know more about the pendulum motion. She asked: “Did we learn about pendulum motion in middle school physics?” After hearing as I replied, “Yes!” She further added, “I don't remember anything about pendulum motion." Despite not recollecting learning pendulum motion in high school, she answered the interview questions correctly. It seemed her participation in the experiment improved her learning, though she might need to understand the underlying knowledge centred around pendulum motion.

In summary, three of the five interviewees saw the mathematical equation as the key to understanding pendulum motion. Two of them somehow changed their views about the effective factors in determining the swing period of the pendulum motion. The third one even commented on the mathematical aspect of this equation. In contrast, it seems that the other two interviewees have lost meaningful contact with the equation and did not get too much from it.

Summary of Qualitative Results

In this chapter, the juxtaposition of students' interview accounts provides complementary insights into how the overlapping distributions of pendulum knowledge were represented, conceived, expressed, or even changed at the level of verbal evidence. These interconnected narratives also present a fuller picture of the implications for the interviewees' understanding of the empirical equation $T= 2\pi \sqrt{l/g}$, the mathematical identity of the oscillation period of a simple single pendulum and its boundary condition.

To summarize their responses, I extracted a unique quotation from each interviewee to characterize their experiences with the pendulum motion. To the first interviewee, physics knowledge is "pretty amazing." The second interviewee viewed the parameters in the mathematical equation as "fixed quantities." To the third interviewee, his identification with pendulum motion is through "a half-power exponential function." For Interviewee #4, physics is her "weakest subject." The last interviewee said she had "forgotten pendulum knowledge." From the qualitative data analyses, it is clear that they have commonly expressed interest in understanding pendulum motion and foregrounding their connections with physics knowledge. In the next chapter, I discuss the key findings of the proposed active learning mechanism in the PER.

CHAPTER 9 DISCUSSION, CONCLUSION, AND IMPLICATIONS

The last three chapters have documented at least two types of evidence to highlight the organizing role of the mathematical identity expressed in students' sampling and decision-making in the pendulum period-matching and explaining tasks. The time has come to restate the thesis that conceptual change can be viewed as an active S-D process over an overlapping knowledge distribution in students' conceptual spaces. Whether in the intuitive or counterintuitive information processing or in the overlapping middle area of the represented knowledge distributions, the probability is the key to unlocking what has changed or not. By embracing a probabilistic frame of reference, I have proposed in this study to advance conceptual change in science education by holding tight to the mathematical definition of a physics concept and embodying the caveat "Don't throw the baby out with the bathwater!" In the two experiments and the interviews, the role of the mathematical definition of a physics concept in organizing these participants' conceptual spaces has been revealed through a pendulum period-matching task, which is complemented by the interviewee's verbal expression of understanding such a mathematical identity. In this chapter, I take a closer look at how to re-integrate a mathematically defined physics concept (such as $T = 2\pi\sqrt{l/g}$) in acting conceptual change learning with the verbal expressions included. Finally, I revisit the research questions and reflect on the pedagogical implications of these findings.

A Mathematically Defined Physics Concept: Friend or Foe?

Interestingly, most current conceptual change studies except PER choose to avoid the mathematical contents (Potvin & Cyr, 2017). For example, Andrea A. diSessa (2014) in his *A history of conceptual change research: Threads and fault lines* noted "(t)he conceptual change paradigm is less often applied to other areas of science, and much less in mathematics" (p. 88).

More directly, he later argued that “(u)nderstanding mathematics and its use in science is a worthy topic, but I believe it is secondary to deep qualitative, conceptual understanding” (diSessa, 2017, p. 26). However, the data collected in this study have suggested otherwise, even in the simplest case of matching a simple single pendulum motion task. The most relevant significant factors are those already included in the mathematical equation $T = 2\pi \sqrt{l/g}$. The mathematical expression is, in effect, the mathematical definition of the concept: the oscillation period. Given what I observed in the experiments and the interviews, the participants struggled to understand such a mathematically defined physics concept with their ordinary senses.

When the boundary condition of a small initial release angle has not been met, only mathematical or experimental knowledge, rather than other types of verbal expressions, can provide a satisfactory explanation. In this aspect, I concur with Bruce L. Sherin when he commented on the conceptual physics program (Hewitt, 1971) or the similar Physics for Poets (March, 2003). He contested,

> I challenge the assumption that in physics or any domain the conceptual and the symbolic elements (the mathematical identity or definition) of a practice can be separated for the purposes of instruction. Removing equations from the mix changes the nature of understanding. This does not imply that physics cannot be taught without equations. However, it does imply that equation-free courses will result in an understanding of physics that is fundamentally different from physics as understood by physicists. (Sherin, 2001, p. 524)

However, the question remains why the equation-free PER would be different. Without a new theoretical framework, uncertainty remains. As introduced in Chapter 4, I have attempted to draw a wider picture of conceptual learning that centers on a psychologically plausible and probabilistic mechanism: the sampling and decision-making over an overlapped knowledge distribution. In this S-D framework, the sampling process provides a front end for the mind to take in new information, whereas the decision-making drives the learning outcomes. If this assumption is reasonable and correct, it implies that the equation-free physics learning programs or the conceptual change at the verbal level only promote a biased sampling strategy while leaving relevant mathematical contents out of the equation. I argue that mathematical elements are inevitable to understand learner sampling and decision-making fully.

In general, using the mathematical form departs from the established conceptual change research traditions rooted in the philosophy of science, which may result in interpreting the history of science in a new light, especially when the philosophical tradition may sometimes become misleading. Alan Chalmers, in his *The Scientist's Atom and the Philosopher's Stone: How Science Succeeded and Philosophy Failed to Gain Knowledge of Atoms* (2009), has reminded science education researchers that losing the experimental contact with reality had failed the philosophical atomism as a general heuristic conceptual structure to maintain a productive role in guiding modern atomic physics research. If the fate of philosophical atomism has revealed something soberingly informative, it also reminds conceptual change researchers not to lose mathematical and experimental contact with reality.

Following such a conviction, I have assembled four new theoretical constructs into a new theory of conceptual change. Here, I put them into another conceptual change matrix featuring a probabilistic frame of reference. In other words, a stochastic element can be found in each component of such a construct, such as the binomial distribution-like structure, yoking students' intuitive and counterintuitive ideas in their conceptual spaces. The conceptual "yoke" connects or joins the misconceptions and an anchoring physics equation together in a more general sense. Either the misconception- or the anchoring equation-based distribution each has its central tendency and variances. Learning in such a conceptual space can be characterized by sampling and making-decision about the possible next move in a problem subspace. Sometimes, sampling and decision-making would be reconfigured to solve the new problem. Also, in this conceptual framework, the learning outcomes could be a miss, hit, false positive, or correct rejection. Commonly, these theoretical constructs feature mathematical connections.

Viewed from such a theoretical lens, I add a new layer of meaning to the concept of change. The change in the conceptual space is reinterpreted as establishing a unique tendency to sample from an anchor equation- (Redish, 2021) or symbolic form-based (Sherin, 2001) knowledge distribution in a conceptual space rather than doing that from an intuition-based knowledge distribution. The sampling tendency upgrading can also explain what I have observed in this study. For example, the time position effect of a candidate pendulum, as observed in Experiment 1, can be explained as more rounds of sampling would be needed for the first candidate pendulum due to its temporal position in the series of the to-be-matched pendulums. The length effect of the rod pendulum can also be interpreted similarly. Most importantly, the amplitude effect of the initial release angle of a candidate pendulum has also confirmed the S-D assumption.

In addition to the new interpretations of the experimental effects, the theoretical lens also adds a new angle to interpret the quantitative conceptual change studies reviewed in Chapter 3. Take Babai and his collaborators' (2006) study of counterintuitive reasoning as an example. When the mental chronometric measures were first introduced, they were based on the following rationale: intuitive reasoning would be faster than counterintuitive one. Thus, a selection process driven by intuitive reasoning should have a shorter reaction time than one driven by counterintuitive reasoning. However, they did not explain why intuitive reasoning could be faster. Given the S-D framework, their results can be interpreted as the sampling from intuitive knowledge distribution is faster.

In contrast, another sampling from a learned-rule-based knowledge distribution would be slower. As the new theoretical lens relied on the science of probability, it connects conceptual changes studies with the mathematical psychologists' stance of viewing learning as representing meaningful information or signals in the brain as a random variable in memories (Luce, 1992; Swets et al., 1961; Thurstone, 1930). The connection also links the cognition-as-intuitive-statistics (Gigerenzer & Murray, 1987) view of higher-order thinking. All in all, the new probabilistic S-D framework opens new possibilities for conceptual change researchers.

The Sampling Side of Conceptual Change

As introduced in Chapter 2, Paul Thagard, in his synthesis *Concepts and Conceptual Change* (1990), described his theory of the degree of conceptual change. The theoretical construct can be seen as an early instance of the probabilistic approach to the conceptual change problem, which has been characterized as a sampling and decision-making process. His knowledge tree switching or jumping can also be reconceptualized as establishing a new sampling and decision-making in a conceptual space.

The S-D theoretical framework also sheds light on the non-typical students' conceptual change issues. As introduced in Chapter 2, Zhou's (2012) conceptual advancement was proposed to make a co-existent status of misconceptions and scientific understanding possible. To achieve this goal, he aligned his notion of conceptual advancement with the collateral learning perspective (Jegede, 1997). He illustrated the idea with his personal experience of commuting between Windsor (Canada) and an American city. The border-crossing experience is not interpreted "as a simple sum of the original A and B (city), but a combination of two" (p. 119); Therefore, "a *third entity* (emphasized by the author) or *third space* is necessary to guide our understanding of this topic" (p. 120). Such a description has a natural interpretation if an overlapping intuitive and non-intuitive knowledge distribution has been assumed. Seeing through such a theoretical lens, I have extended Zhou's hybrid learning space (2012) toward a multinomial distribution-filled space, where a learner is free to sample from any of these knowledge distributions and decide afterward. Besides its reinterpretation of the hybrid learning space, such a perspective is also ready to be implemented to extend Nashon and Anderson's contextualized science learning experiences (2013), which connect the African informal manufacturing sector and school science by adding a probabilistic dimension.

Similarly, other major conceptual change theoretical frameworks summarised by Potvin and his colleagues (2017) can also be reinterpreted with the probabilistic frame of reference. Due to adding a 2 × 2 learning outcomes matrix in the proposed theoretical framework, this S-D framework can be readily applied to measuring conceptual change tasks. This study has demonstrated such a benefit through the two-pendulum motion period-matching experiments. Most importantly, the statistical analysis techniques have relied on the same notion of probability and margin of error. In this sense, a unifying conceptual framework has been developed through the two experiments and the interviews.

The Decision-Making Side of Conceptual Change

Some yoked intuitive and counterintuitive conceptions are best represented or modelled using a conceptual problem space with more than one probabilistic frame or dimension. In the two- or three-dimensional event, such as deciding the oscillation period of pendulum motion, each round of the sampling leads to a distribution taking on parameters or values of the likelihood for pairs of or a triple of information packages. In an experimental context, the participant often established a decision boundary to divide the pendulum motion space into regions corresponding to each possible matching response.

In seeing the selection prompt, the task was to match the period given the standard pendulum, saying “yes” to the presentation of a simultaneous cheek-large-initial-release-angle pair and “no” to no presentation or irrelevant information on both physical features. A variety of such decision rules can be considered for characterizing the decision-making aspect of conceptual change: (a) the independence of each frame of such a decision, in which only the value of likelihood of one dimension is thoroughly sampled; (b) the maximumly yoked principle, in which two larger-than-a-cut-off judgments would be required on both dimensions; (c) the minimally yoked principle, in which either the presence of a cheek or an initial release angle is required; and (d) an optimal sampling integration principle, in which an ideal decision parameter is obtained by summing or multiplying the sampling results of the two dimensions. The results observed in the two experiments can be interpreted as the participants implementing these principles to the oscillation period-matching task in their conceptual spaces, which had characterized the task in their own ways.

A similar vein can also be found in the qualitative study. As introduced in Chapter 4, a learner’s verbal evidence forms the second level of the proposed taxonomy of physics knowledge. Below the verbally defined level and at the bottom of the upward swing are the physical objects, natural processes, and simple events of our world that occurred naturally, without any form of symbolic processing in any language. On these sensory and perceptual experiences of a physical pendulum, there comes the symbolization of such experiences with various language forms, such as those expressed in English or another language. Following this level, error-term-characterized empirical observations are represented as half mathematically and half verbally defined as raw scientific data. At the top of such a taxonomy sits the structural realist's mathematical core: T= 2 π $\sqrt{l/g}$ for small swing amplitudes and the fundamental natural phenomenon hidden behind the veil of so-called "reality": an isochronous simple harmonic oscillator.

Similarly, Ronald Giere (1994) put forward a partial conceptual map of classical mechanics with the five levels of physics knowledge. According to this knowledge map, the visual models, which correspond with my visual experiences of the new taxonomy, of free fall, the motion along an inclined plane, pendulum swings, spring oscillation, moving in a circular orbit or an elliptical orbit are located at level V. Checking his levels IV and III, he suggested that "pendulums are not the only species of harmonic motion—a bouncing spring may be an even more central case of harmonic motion than a pendulum" (p. 288).

Also, according to the same researcher of the cognitive structure of scientific theories (Giere, 1994), the harmonic motion with linear restoring force ($F = -kx$) is listed side by side with the other two types of motions: 1) the rectilinear motion with a constant force ($F\ remain\ the\ same$) and 2) the orbital motion with inverse square force ($F = k/r^2$). Above these two levels are conservative and non-conservative types of mechanical models. Commonly, they belong to the classical mechanical models. Such a knowledge structure helps form a basis of a conceptual foundation for interpreting the students' verbal expressions.

In 2014, the ninth International Conference on Conceptual Change was held in Bologna, Italy. Among the conference presentations, Susan Gelman and Jasmine DeJesus put forward a unique perspective on the uses of language in science education: "Words invite and impede conceptual change" (2018, p. 89). I build on the suggestion to summarize the interview data I have observed so far by foregrounding the distinction among a false-positive, correct rejection, hit and miss in identifying the weight, length, and initial release angle of the gasket-based pendulum as the effective factor to determine its swing period in a cycle of going from the highest point to its lowest, and coming back again to its original release point.

Among the five interviewees, none of them have shown a fully integrated idiosyncratic knowledge structure of pendulum motion, as illustrated by Ronald Giere (1994) and Michael Matthews (2000). Instead, the verbal evidence can be readily viewed as the verbal manifestations of the fragmented knowledge pieces (P-prims) introduced by Andrea diSessa (1993). However, diSessa's P-prims are inarticulate, whereas interviewees somehow mapped their (mis)conceptions to a set of full or partial sentences of their first language. To me, they are also probabilistic. A better way to characterize such verbal evidence is to apply the 2×2 conceptual change matrix. In so doing, the misconception of the weight and initial release angle in determining the period can be re-interpreted as a false positive identification, whereas identifying the length of the pendulum string as the factor is a hit on the accepted classical mechanical knowledge structure.

As predicted from such a perspective, the false positive identification of the weight and initial release angle as the effective factor in determining the period of pendulum motion has been observed in all the interviews except the third one. The exception of the third interviewee has been achieved by her or his relying on using the mathematical identity of the pendulum' period in answering the interview questions. A similar tendency has also been observed from the first and the second interviewees when the equation was shown to them. It seems the mathematical equation achieved some "magic" effects in reorganizing their fragmented knowledge pieces. Such an organizing effect has not been observed in the other two interviewees, who claimed they had forgotten their high-school physics knowledge.

Unlocking the Learning Brain's Active Sampling and Decision-making

In today's parlance, the brain relies on a network-like structure (Baronchelli et al., 2013) to enable us to sample and make a decision, thus changing conceptions. Such a neural network has often been approximately characterized by its components and connections: neurons and synapses (Dehaene & Naccache, 2001; Salmelin & Kujala, 2006). As we know, a single neuron affords the basic cell-level information processing unit. Its conception was conceived more than 100 years ago by Santiago Ramóny Cajal (Haines, 2007), who first identified the independent cellular structure of a neuron. Following his lead, Adrian and Bronk (1929) associated neurons' spiking patterns with the axonal and dendritic mechanisms. Later, Hodgkin, Huxley, and Eccles (1963) demonstrated the ionic mechanisms inside and outside neurons' membranes. Together, these single neuron-based mechanisms demystified the brain's neural impulse trains - the information-carrying mechanism of human cognition. Regardless of describing or explaining axonal or ionic neuronal mechanisms, time is a fundamental aspect of them (Mesulam, 1998; Muller, 2000; Palva & Palva, 2012), which implies time is essential for understanding learning.

The importance of time in understanding the brain's language of information processing can be found beyond the single neurons. In effect, it also has implications for other neuronal structures, such as (a) the supportive glial cells-based mechanisms (Fields et al., 2013), and (b) the synaptic (neuron-to-neuron) chemical information transmission processes (Bennett, 2000). First, the glial cells separate the myelinated axonal fibres from the unmyelinated ones. According to Fields et al. (2013), the glial cell-based mechanisms are still largely absent from thinking about representing and processing information because the glial cells do not generate electrical impulses. However, they form crucial cell-cell interaction that shapes the cellular mechanisms of learning and cognition. More importantly, they couple neurons into functional units for short-term and long-term information storage and transformation, thus enabling learning and cognition. In other words, learning is in time.

Furthermore, time is also involved in inter-neuronal connections. As for the chemical agent-based neuron-to-neuron communication, the specialized neuronal structure at the axon terminal is called a synapse (Debanne, 2004; Fields et al., 2013; Langille & Brown, 2018), the gap for diffusing and relaying neurotransmitters from one sending neuron to a receiving one. The diffusion process starts by releasing the functional molecules from pre-synaptic neurons' membranes into the synaptic gap. Over the gap, the ionic channels of post-synaptic neurons would enable a membrane-fusing process, binding these molecules in a lock-and-key manner. The binding thus opens and closes the membrane ionic channels. The exchange would permit some kind of neuron-to-neuron information transmission, spreading neuronal information forward in a neuronal network. The three components (single neurons, glial cells, and synapses) help form a neuron-based information processing network in the central and peripheral neural systems. As for learning and cognition, small neocortical networks form large-scale neural networks to support reshaping the dynamics and structures of such a network (Gastner & Ódor, 2016). Again, the brain processes information in time

Such a vast time-based information processing network is necessary for researchers to conceptualize problem-solving, conceptual change, and metacognitive processes. One powerful way to characterize the synaptic connection-based structure is to use a hierarchical structure for a functional approximation. For example, Mesulam (1998) introduced six degrees of synaptic separations to capture the essence of such a network (i.e., its primary sensory-motor function, unimodal associative representing function, and hetero-modal associative and the paralimbic and limbic representing function).

More specifically, the primary sensory-motor function of such an information processing network interfaces the initial processing of "raw" sensory inputs and the generation of behaviourally significant responses. Close to it, the unimodal associative function of the network maintains the fidelity of the "raw" sensory inputs. In contrast, the hetero-modal associative function of the network serves to provide a cross-sensory-modality representation of the input data. At last, the paralimbic and limbic functions provide reciprocal access to the hypothalamus. Collectively, such a characterization offers a framework to ground cognition. In other words, cognitive processes are defined as the neural information processes between the obligatory processing of "raw" sensory inputs and the generation of behaviourally significant responses in such a network. Meanwhile, cognitive processes manifest contextual effects, memory guidance, and other task-bound constraints realized in the network. Again, the brain's information processing over six degrees of separation can be seen as a conceptional change process that occurred in time. These considerations contribute to building a solid scientific foundation for reconceptualizing conceptual change through active sampling and decision-making.

Conclusion and Pedagogical Implications

In two experiments, participants' pendulum period-matching was measured in the rapid serial presentation format by varying a range of factors. To my knowledge, this is the first study that has demonstrated how to measure it and the first study that has given an initial estimate of its magnitude. In addition, five interviews were conducted to explore international students' understanding of the pendulum motion and their impressions of the mathematical equation T = $2\pi\sqrt{l/g}$. The results have also confirmed that participants' knowledge of pendulum motion could be improved by their understanding of the mathematical identity of the oscillation period of a pendulum and the boundary conditions in their applications. Commonly, they have pointed out a unique structure of intuitive and nonintuitive in their mind: an overlapping binomial distribution-like conceptual structure.

The binomial distribution-like knowledge structure has unique characteristics that distinguish it from those verbal definitions of a conceptual change space. Specifically, it exhibits an overlapping middle area encompassing intuitive and non-intuitive knowledge. It can explain conceptual change as a sample and decision-making process within this conceptual space. Given such a theoretical construct, the conceptual change process can be viewed as a time-based procedure with a different sampling tendency over the knowledge distribution. While a complete understanding of conceptual change remains elusive (Posner et al., 1982; Thagard, 1990; Babai, Levyadun, et al., 2006b; Zhou, 2010, 2012a; Potvin et al., 2020; Nashon, 2004), this study has provided a unique and informative reference point for future research into the active sampling and decision-making mechanisms involved in conceptual change.

Foregrounding the unique aspect of physics concepts and a new taxonomy of concepts has significant pedagogical implications. First, it helps generate a shift in the fundamental approach and assumption of the field. At present, the dominant view of conceptual change pedagogies is derived from a replacement view of conceptual change. The overlapping distribution of intuitive and nonintuitive knowledge suggests this is impossible. In this sense, how to guide students effectively in sampling a new knowledge distribution and learning to make a new decision became more important. The mathematically defined concepts serve such a function better than other forms because they highlight a concept's most relevant theoretical components while shedding off irrelevant distracting information. When the requirement of memory loading is high, such a compact information guide can create a more effective sampling process and promote a decision in the right direction. The potential of exploiting such pedagogical usage is worth further exploration.

Second, the new taxonomy of physics concepts reconnects science teaching and learning with its historical roots. Michael J. Crowe, in his *A History of Vector Analysis: The Evolution of the Idea of a Vectorial System,* depicted a hidden connection between mathematics and physics. After introducing the history of searching for the concept of numbers, he added,

> The second tradition, that within the history of physical science, also extends back to ancient times and consists in the search for mathematical entities and operations that represent aspects of physical reality. This tradition played a part in the creation of Greek geometry, and the natural philosophers of the seventeenth century inherited from the Greeks the geometrical approach to physical problems. However in the course of the seventeenth century the physical entities to be represented passed through a transformation. This transformation consisted in the shift in emphasis from such scalar quantities as position and weight to such vectorial quantities as velocity, force, momentum, and acceleration. The transition was neither abrupt nor was it confined to the seventeenth century. Later developments in electricity, magnetism, and optics acted further to transform the space of mathematical physics into a space filled with vectors. (Crowe, 1985, p. 1)

Such a historical connection is rarely mentioned in conceptual change studies. However, the physical sciences were developed by introducing these mathematical ideas. Avoiding these contents to attract students is not always the best pedagogical strategy. Instead, using the new taxonomy that features the mathematical connection is the first step in the right direction.

Third, the new taxonomy also bridges the gap between conceptual change studies and laboratory teaching and learning sciences. As demonstrated in this series of experiments, experimental design and data analyses are based on the notion of probability and the distribution of random errors. Emphasizing the mathematically defined concepts and conceptual change also helps establish the link with these laboratory routines. With the aid of these physics laboratory-related contents, it would be easier to clarify scientific contents presented in textbooks, understand solutions to problems, and demonstrate underlying scientific principles. In this sense, the new taxonomy provides a probabilistic framework for organizing and categorizing students' knowledge in a more psychologically natural way. It recognizes that concepts are in the process of dynamic sampling and decision-making over overlapping knowledge distributions and that science learning is an ongoing process. By using this taxonomy, conceptual change researchers can help their students develop a deeper and more meaningful understanding of scientific concepts, especially through their connections with mathematical identities.

In brief, the new taxonomy with a probabilistic frame of reference significantly contributes to extending Zhou's hybrid learning space (2012) by establishing meaningful connections and offering opportunities to understand international students' science learning experiences in verbal expressions and their reaction times. It recognizes that these international students come to the science classroom with intuitive pre-instructional ideas, which may be inaccurate or incomplete given mutually accepted scientific understanding and practice. By seeing these misconceptions as sampling and decision making, science educators can have a conceptual handle to help students resample and make a new decision, thus promoting a more accurate and comprehensive understanding of scientific concepts.

Moreover, foregrounding the role of a matrix of event, propositional perception, and mathematical functions in influencing students' real-time responses help to reconnect sociocultural conceptual change studies with the structural realist's outlook of the fundamental science and science education (Chalmers, 1999; Matthews, 2015; Mayer, 2004; Rowbottom, 2019). Furthermore, the results of this study help promote a new line of discussion of measurement theories in conceptual change studies. Most importantly, the evidence has confirmed the co-existing view of students' intuitive ideas and the scientific notion of pendulum motion, as advocated in the conceptual advancement view of conceptual change (Zhou, 2012). Such evidence will further support the student-centred approaches in PER, which let students speak out their intuitive ideas first; and then offer culturally and linguistically appropriate feedback to improve their science learning (Zhou, 2010).

The conceptual change view of science learning is not new, but a new taxonomy based on concepts and conceptual change is, especially when considering culturally and linguistically diverse international students' learning experiences. Although the probabilistic taxonomy has not been explicitly discussed before, similar ideas have been explored in the intersections of conceptual change studies (Duit & Treagust, 2003; Potvin et al., 2020; Thagard, 1990; Zhou, 2010), the second language learning research (Li et al., 2021; Li & Zhou, 2007; Li & Wong, 2021; Li, 2016), and domain-specific teaching and learning (Mayer, 2004).

The classificatory scheme helps researchers refocus on what culturally and linguistically diverse international students really bring to Canadian science classrooms. More importantly, the taxonomy promotes more generalized thinking in science education, seeing previous separate conceptual change studies as special cases of reweighting personal knowledge distributions. Although it is always challenging to characterize a still-evolving research field, reviewing some fundamental aspects of conceptual change studies still helps us consolidate what we have learned so far.

What are the roles of a mathematically defined physics concept (such as $T = 2\pi\sqrt{l/g}$) in influencing the sampling and decision-making processes in human reaction time during learning by which international students use to change their concepts in science learning? The mathematically defined physics concept (such as $T = 2\pi\sqrt{l/g}$) first keeps the only relevant factor activated in the mind when a student samples or makes a decision. When activated in advance, such a conception guides the student to select and focus on relevant information and examples that align with such a mathematical identification. Also, it impacts the decision-making processes by shaping their judgments in the direction of the proportional relation between the period of a pendulum and its length. Such a mathematically defined physics concept can support an updated cognitive framework that induces and influences learning. Next, how can the effects of such a S-D mechanism be measured non-verbally? These two experiments demonstrate that it can be measured in human reaction time-based experiments using priming mechanisms-based techniques. By analyzing the reaction times and error rates, education researchers can gain insights into how such a conception influences the sampling and decision-making processes. Last, what are the pedagogical implications of using the new taxonomy? On the one hand, teachers can design instructional activities that explicitly integrate the mathematically defined physics concept into science lessons. By doing so, international or local students can better understand the physics concept and its role in influencing their reasoning. On the other hand, science educators can encourage their students to sample more knowledge types and be open-minded in making a decision when navigating the complexities of the hybrid conceptual space and its applications in real life.

The pedagogical implications of such a probabilistic cognitive “revolution” are manifold: (a) the probabilistic re-orientation can enhance science students', domestic or international, understanding of scientific concepts and scientists’ conceptions. By using mathematically defined conceptual tools, the students can gain a deeper understanding of scientific concepts that may have previously appeared difficult to comprehend. The new taxonomy allows students to view scientific concepts and conceptions through a physics-compatible lens, which can significantly help clarify the underlying theoretical principles and the organizing key notions; (b) the new taxonomy helps guide new curriculum design endeavours to bridge the gap between abstract mathematical concepts and their physical interpretations. In the tradition of conceptual change studies, physics education research has relied heavily on qualitative approaches to understanding physical phenomena, often overlooking the importance of idealized quantitative reasoning and its error terms. By incorporating sampling and decision-making theory into physics education research, researchers and students alike are more likely to appreciate a deeper understanding of the underlying mathematical structures that govern physical phenomena, which entails conceptional change; (c) the taxonomy and its experimental manifestations deliberately promote a positive attitude toward the interdisciplinary learning since the experimentation and statistical modelling are not limited to physics research alone, and many other fields such as mathematical psychology, artificial intelligence, and educational assessment depend heavily on mathematical reasoning. By incorporating the new taxonomy into the researchers’ teaching practices, they, in effect, help develop the student's skills necessary to apply scientific and mathematical reasoning across a wide range of disciplines.

A Caveat on the Limitations of the Current Study and Future Research

This study was designed when the COVID-19 pandemic was still affecting every aspect of students' lives. One limitation of this study is its lack of an interactive component in the pendulum period-matching task. Therefore, these two experiments have not fully explored the participants' active learning. Further studies should consider the possibility of adding such a component as a participant self-controlled matching procedure. It will be informative to find out whether their active exploration would increase their response times.

The absence of an emotional component is the second limitation of the current study. Since the publication of *Beyond Cold Conceptual Change: The Role of Motivational Beliefs and Classroom Contextual Factors in the Process of Conceptual Change* (Pintrich et al., 1993), the emotional aspect of conceptual change processes has attracted scholars' attention. For some non-math students, their motivational and emotional experiences may significantly influence their conceptual change learning. Future experiments should explore this possibility.

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APPENDIX A R COMMANDS USED IN EXPERIMENT 1

```
# Load required packages (these may need to be installed)
library(readr)# For importing data
library(lme4)# For GLMM modelling
library(jtools)# For helpful model summaries
library(rempsyc)# For exporting results

# Importing a simulated data set
cc_Raw <- read_csv("C:\\Data\\exp1.csv")
head(cc_Raw)

#A logistic GLMM-modeling of Experiment 1 data set with #position and length
as the predictors and corrAns as the #criterion
cc1 <- glmer(corrAns ~ position + length + (1|id),
        data = cc_Raw, family = binomial,
        control = glmerControl(optimizer = "bobyqa"),
        nAGQ = 10)
summary(cc1)
summ(cc1, exp=T)

#A second GLMM-modeling of Experiment 1 data set with #weight added as a
new predictor
cc2 <- glmer(corrAns ~ position + length + weight + (1|id),
        data = cc_Raw, family = binomial (link="logit"),
        control = glmerControl(optimizer = "bobyqa"),
        nAGQ = 1)
summary(cc2)
summ(cc2, exp=T)

#A third GLMM-modeling of Experiment 1 data set with
#the participants' reading level added as a new predictor
cc3 <- glmer(corrAns ~ position + length + weight + reading+(1|id), data =
        cc_Raw, family = binomial (link="logit"), control = glmerControl(optimizer
        = "bobyqa"),  nAGQ = 1)
summary(cc3)
summ(cc3, exp=T)


# Nested Models Comparison
                    anova(cc1,cc2,cc3,test="Chisq")
```

APPENDIX B R COMMANDS USED IN EXPERIMENT 2

```
# Load required packages (these may need to be installed)
library(readr)# For importing data
library(lme4)# For GLMM modelling
library(jtools)# For helpful model summaries
library(rempsyc)# For exporting results

# Importing a simulated data set
cc_Raw <- read_csv("C:\\Data\\exp2.csv")
head(cc_Raw)

#A logistic GLMM-modeling of Experiment 2 data set with #position and cheeks
as the predictors and corrAns as the #criterion
cc1 <- glmer(corrAns ~ position + cheeks + (1|id),
        data = cc_Raw, family = binomial,
        control = glmerControl(optimizer = "bobyqa"),
        nAGQ = 10)
summary(cc1)
summ(cc1, exp=T)

#A second GLMM-modeling of Experiment 2 data set with #weight added as a
new predictor
cc2 <- glmer(corrAns ~ position + cheeks + angle + (1|id),
        data = cc_Raw, family = binomial (link="logit"),
        control = glmerControl(optimizer = "bobyqa"),
        nAGQ = 1)
summary(cc2)
summ(cc2, exp=T)

#A third GLMM-modeling of Experiment 2 data set with
#the participants’ reading level added as a new predictor
cc3 <- glmer(corrAns ~ position + cheeks + angle + reading+(1|id), data =
        cc_Raw, family = binomial (link="logit"), control = glmerControl(optimizer
        = "bobyqa"),  nAGQ = 1)
summary(cc3)
summ(cc3, exp=T)

# Nested Models Comparison
anova(cc1,cc2,cc3,test="Chisq")
```

APPENDIX C INTERVIEW QUESTIONS IN THE ORIGINAL FORMAT

单摆运动访谈

介绍单摆的概念。

1.请您列举几个在生活中见到过的单摆的实例

2. 请问影响单摆摆动的力是什么？

3. 当钟摆偏离其平衡位置时，您认为是什么导致它又移回该位置？ （力， 能量）

介绍周期的定义

4. 您认为摆锤的重量影响单摆的摆动吗？

5. 你认为摆锤的重量会影响单摆的周期吗？那如何影响呢？

6. 你认为摆线的长度如何影响单摆的摆动？

7. 你认为摆线的长度会影响单摆的周期吗？那如何影响？

8. 您认为释放角度如何影响钟摆的摆动？

9. 你认为单摆的释放角度会影响单摆的周期吗？那如何影响？

10. 从公式 $T=2\pi\sqrt{l/g}$， 你能看到什么？你是如何理解这个公式的？

11. 如果你发现钟摆慢了，该如何调整摆锤下面的螺母？向上还是向下旋动？

12. 关于钟摆运动，您还有什么想了解和补充的吗？

APPENDIX D INTERVIEW ON THE SINGLE PENDULUM MOTION (ENGLISH TRANSLATION)

1. List a few examples of pendulums that you have seen in your life.

2. what is the force that affects the oscillation of a pendulum?

3. When a pendulum moves away from its equilibrium position, what do you think causes it to move back to that position? (force, energy)

4. do you think that the weight of the pendulum affects the oscillation of the pendulum?

5. Do you think that the weight of the pendulum affects the period of the pendulum? How does it affect it?

6. How do you think the length of the pendulum affects the oscillation of a single pendulum?

7. Do you think that the length of the pendulum affects the period of the single pendulum? How does that affect?

8. How do you think the angle of release affects the oscillation of the pendulum?

9. Do you think the angle of release of a pendulum affects the period of the pendulum? And how does it affect?

10. What can you see from the equation $T= 2\pi\sqrt{l/g}$? How do you understand this equation?

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