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GESTURES AS A TOOL FOR RESEARCHERS: WHAT THE HANDS REVEAL ABOUT NOVICES AND EXPERTS' ONTOLOGICAL CATEGORIZATION THAT LANGUAGE DOESN'T

by

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AN ABSTRACT OF THE THESIS

Mariam Mohamad Yamout for Masters of Arts

Major: Education

Title: Gestures As A Tool For Researchers: What The Hands Reveal About Novices And Experts' Ontological Categorization That Language Doesn't

Many studies in the field of "conceptual change" focus on exploring the nature of learner conceptions and how concepts differ across different levels of expertise. In the 1990s, Chi and colleagues developed the Ontological Shift theory (Chi & Slotta 1993; Chi, Slotta, & de Leeuw, 1994). They proposed that learners incorrectly categorize science concepts into the matter category while experts would categorize these concepts into the process category. From this perspective, learning requires that novices undergo a recategorization of scientific concepts, shifting these concepts from the matter to the process ontological categories. In contrast, proponents of a dynamic ontologies view have argued that learners possess a wide range of resources, with ontological metaphors considered among these resources that learners activate when thinking about science (Amin, 2009, Dreyfus et al., 2014). The current study is, in part, a replication of the study conducted by Slotta et al. (1995) while adding gestures as an analytical lens onto novices and experts' ontological categorization alongside the use of language as a source of information about learner and experts' ontological categorization. Specifically, this study aimed to examine whether the analysis of gestures (alongside speech) can be used as a productive method to identify learners and experts' ontological categorization of science concepts. It also aimed to identify whether the analysis of gestures and speech indicate the same or different ontological categorizations. Participants were provided with multiple choice problems targeting the science concepts heat, light and electric current and they were requested to formulate explanations of the outcomes they predicted in each case. The analysis of participants' verbal explanations revealed that in the context of their explanations, experts more frequently categorized the target science concepts as a process while novices categorized them as material substances. This supports to a certain extent the theoretical position held by proponents of the Ontological Shift theory. Yet, the analyses of gestures revealed how gestural predicates – which were primarily spatial and involved coordination of a variety of material substance metaphors – frequently indicated material substance ontological categorizations of a science concept even by experts. Therefore, in expert explanations, speech and gestural predicates were often inconsistent with one another. Overall, these findings (especially in relation to experts) show that ontological metaphors are activated and coordinated and can be considered among the resources that support thinking of abstract science concepts as a process. This supports the theoretical position held by proponents of the dynamic view of ontology. As such, the study concluded by proposing an intermediate perspective which suggests that the shift toward greater expertise (i.e., conceptual change) entails refinement as well as radical restructuring where various metaphors are coordinated leading to the construction of a process ontological category. Such

theory implications have implications for the design of instruction which entails using symbolic representations and designing activities that support the development of process ontological category.

CONTENTS

Appendix

ILLUSTRATIONS

Figure Page

TABLES

Table Page

CHAPTER I

Introduction

Background and Rationale

"Conceptual change" is an approach to science education research which focuses specifically on students' initial conceptual understanding and the changes that take place during instruction. Researchers investigate the nature of students' conceptions and the reason why some misconceptions are robust. Additionally, they study the sources of difficulty students face in learning and the instructional strategies deemed sufficient to overcome these difficulties. More specifically, 'change' refers to transformation in learners' prior knowledge. However, concepts and 'conceptions' are characterized differently by researchers depending on the degree to which they view learners' conceptions to be coherently structured (Amin, Wiser, & Smith, 2014). One of the issues that research on conceptual change has addressed is how students (or generally novices) and experts categorize science concepts. Specifically, two contrasting views exist regarding the role ontological categorization in conceptual change: The Ontological Shift (OS) theory developed by Chi and colleagues; and the dynamic ontological view developed by Gupta, Hammer and others.

In the 1990's, Chi and colleagues developed the OS theory of conceptual change (Chi & Slotta 1993; Chi, Slotta, & de Leeuw, 1994). This theory builds on the work of Keil (1979), which highlighted the role that ontological categorization plays in concept learning. Keil defines ontological knowledge as "one's conception of the basic categories of existence, of what sorts of things there are." (p. 1). For example, a cow is an animal, so it belongs to the animal category which belongs to the higher-order matter category. However, a football match is an event that belongs to the event category, a category that is ontologically distinct from the matter category. Thus, saying “a cow is heavy” [1] or “the rock is heavy” is appropriate since “is heavy” is a predicate which characterizes concepts that belong to the matter category. Yet, saying “the football match is heavy” doesn’t make sense since “is heavy” is a predicate that describes concepts that belongs to the matter category and does not apply to the event category.

Similarly, Chi and colleagues proposed that learners’ conceptions are organized in a hierarchal structure. In which, they argued that novices categorize science concepts into the matter category instead of process category, a distinct category that many science concepts belong to (Chi, 2005, 2013; Chi et al., 1994; Henderson, Langbeim, Chi., 2018; Slotta, 2011). Researchers proposed that this categorization by novices is incorrect and represents a source of difficulty students face in learning some science concepts such as heat, light and electric current. For example, saying “heat can’t get out of the cup” reveals incorrectly categorizing heat into the matter category since “get out” is a substance predicate. This expression reveals thinking of heat as a material substance that is contained in the cup (Slotta, Chi, & Joram, 1995). In contrast, the concept of heat is understood by experts as a process of transfer of energy due to the continuous interaction of molecules. This is revealed in using process predicates such as “is exchanged as molecules collide” and “is transferred as faster moving molecules slow down”. Finally, from this perspective, conceptual change involves an ontological shift as learners *shift* their thinking from the matter ontology to the process ontology.

Chi and colleagues have supported this theory with a number of studies (e.g., Slotta et al., 1995; Slotta & Chi, 2006). Researchers used language analysis to identify the ontological

[1] In this thesis, verbal expressions will be written between quotations “a cow is an hour long”.

categorization of science concepts by novices and experts in the context of them formulating scientific explanations. These studies provided participants with multiple-choice problems where they predicted and explained the outcomes of a certain phenomenon. The results of these studies revealed, that when formulating science explanations, novices frequently use matter predicates while experts frequently use process predicates (Slotta et al., 1995). Consequently, conceptual change is viewed as learners shifting their categorization of a concept from the matter category to the process category and this is evident in their increased use of process predicates when explaining science concepts (Chi, 2005; Chi et al., 1994; Slotta et al., 1995). Building on that, researchers proposed that instruction should confront students' incorrect categorizations and avoid the use of metaphors and analogies that suggest unscientific material substance understandings (Slotta et al., 1995).

An alternative view of students' concept learning suggests that ontological categorization is more dynamic than has been proposed by the OS theory. The dynamic view of ontology proposes that leaners flexibly invoke different ontological categories depending on the context. Proponents of this view indicated the presence of multiple ontological categories unlike what had been proposed by Chi and colleagues who indicated the presence of *two distinct* ontological categories (Dreyfus et al., 2014; Scherr et al., 2012). This was supported by the work of Lakoff and Johnson (1980) on the Conceptual Metaphor theory. This theory claims that metaphors are pervasive in everyday language. For example, saying "I'm *in* love" or "he's *in* a depression" are metaphorical expressions used in everyday language. They reveal construing emotional states as if physically contained at a specific location. But also, saying "I'm *in* love but we are *going* in *different* directions" reveals thinking of love as a journey. This also indicates that the same abstract concept can be conceptualized using different metaphors.

Applying the conceptual metaphor theory to the language of science, Amin (2009) provided evidence that even Richard Feynman (an expert physicist) entertained material substance conceptualizations of abstract scientific concepts. This was based on the analysis of the use of the term *energy* in *The Feynman Lectures on Physics.* Furthermore, Scherr et al. (2012) and Dreyfus et al. (2014) argued that the science concept energy can be construed as an object, as a location, and/or as a force. This is indicated in the Ontological Metaphors that are invoked differently based on context: Energy as a Substance, Energy as a Vertical Location, and Energy as a Stimulus. Researchers supported their inferences based on the analysis of science classroom discourse and science textbooks. For example, when thinking about energy qualitatively, learners and experts think of energy as a substance (e.g., "leaves blowing in the street *have* energy" reflects thinking of energy being a substance stored/contained in leaves). Yet, when thinking about energy quantitatively while using visual representations (e.g., graphs), learners and experts often think of energy as located at a specific location (e.g., "when atoms are pushed closer together, the energy goes *up"* reveals thinking of energy as a location at which the atoms are located (Dreyfus et al., 2014; Scherr et al., 2012). In line with that, researchers have argued for the presence of variability in novices and experts' thinking which supports a dynamic view of ontologies (Dreyfus, Gupta, & Reddish., 2015a; Dreyfus et al., 2015b; Gupta et al., 2010; Scherr et al., 2012).

Proponents of this dynamic view recommend providing learners with an effective learning environment to invoke the right ontological categories in the right context which will often involve the use of various kinds of representations. For example, to help learners understand chemical bonding and energy changes associated with chemical bonding, the use of graphical representations will support understanding the concept of negative energy (Dreyfus et al., 2014; Scherr et al., 2012). Researchers further advocated designing activities that build on a concrete learning environment. This learning environment is characterized by the use of different representations (e.g., computer simulation and the human body itself that represents an energy unit) and manipulation of objects such as ropes. In these activities, teachers/learners embody units of energy as they investigate how energy is transferred and transformed in specific scenarios such as cooling food in a refrigerator (Close & Scherr, 2015; Daane et al., 2018; Scherr et al., 2013). Success of these activities is demonstrated in the teachers developing deeper understanding of how to conserve energy while tracking how energy is transformed and transferred within a system being evident in their interactions.

Disagreement exists between proponents of these two views. Within the last decade, the OS theory has been criticized theoretically and methodologically. Theoretically, it has been suggested that novice's and expert's categorization are dynamic and context-dependent (Dreyfus et al., 2015a; Dreyfus et al., 2015b; Gupta et al., 2010; Scherr et al., 2012). Methodologically, researchers advocating for a dynamic view of ontology suggested that language is used in more complex ways than Chi and colleagues assumed, so it can't simply be viewed as a window onto static ontological categories (e.g., Amin, 2009; Gupta et al., 2010; Jeppsson et al., 2015). On the one hand, Chi and colleagues have argued for the presence of two distinct ontological categories that are not context sensitive. They support their view using a *quantitative* research design where changes in the frequencies in the use of verbal predicates are taken as evidence for changes in categorization (e.g., Slotta et al., 1995). On the other hand, Gupta et al. (2010) provided a *qualitative* case study where they provided examples of novices and experts straddling categories in everyday language and science learning. This was taken as evidence for a dynamic ontological categorization where novices and experts flexibly invoke multiple ontological categories.

However, Slotta (2011) was not convinced that the case study provided by Gupta et al. provided evidence of flexibility. Hammer, Gupta, and Redish (2011) rejected Slotta's criticism and further emphasized the effectiveness of the instructional approach adopted by the dynamic view as it builds on students' productive cognitive resources.

This debate reveals that researchers have not yet reached consensus whether learners and experts' ontological categorization is static as has been proposed by Chi and colleagues, or dynamic as has been proposed by proponents of the dynamic view of ontology. This disagreement is important to try to resolve because it influences which instructional approach is likely to be more effective in overcoming difficulties learners face when learning. Additionally, the debate between researchers reveal the analysis of language has been the main analytical lens used to determine learners and experts' ontological categorizations.

Interestingly, another line of research has used gestures as another analytical lens onto learners and experts' conceptions and reasoning (e.g., Chue, Lee, & Tan, 2015; Cienki & Müller, 2008; McNeill, 1992; Novack & Goldin-Meadow, 2017; Roth, 2001; Scherr, 2008). A significant body of literature suggests that gestures are complementary to speech as a communication channel and they reveal ideas and representations often not articulated in speech (McNeill, 1985, 1992). Gestures are spontaneous movements of the arms and hands that accompany speech (McNeill, 1992). Researchers investigate the gestures produced and their relation to speech in different domains, using different methodologies (qualitative or quantitative), and for different purposes.

A number of studies have investigated how gestures are used in communication. These studies investigated the types of gestures produced in everyday contexts such as expressing scenes from a cartoon movie after watching it (e.g., McNeill, 1985, 1992), or discussing morality (e.g., Cienki and Müller, 2008; Cienki, 2017). Another line of research investigated the use of gestures when thinking and explaining math problems (Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986; Perry et al., 1988) and when learning science in naturalistic contexts (e.g., Roth & Lawless, 2002a; Crowder, 1996a). Data analysis from these studies revealed changes in the gestures produced by students as they are learning. Some identified these changes as changes in the physical form of gestures (Close & Scherr, 2012; Scherr, 2008) or as changes in the relation between gestures and articulated speech (Crowder, 1996a, b; Goldin-Meadow, 2003; Roth & Lawless, 2002b). When investigating these changes, researchers indicated shifts in students' talk or state of ideas from a newly constructed idea to a familiar one (e.g., Crowder, 1996a, b; Scherr, 2008).

In line with the above, two lines of research are highlighted given their adopted methodological approaches. The studies conducted by Goldin-Meadow and colleagues used quantitative analysis to investigate the relation between gesture and speech in the context of solving problems such as mathematical equivalence. The analysis of results revealed that gestures may convey information *different* than that in speech (Congdon, Novack, & Goldin-Meadow, 2018; Goldin-Meadow, 2003). They referred to this as "gesture-speech mismatch". For example, a child's speech may be describing the height of a container while a C-handshape gesture may be referring to the width of the containers. Also, the conducted instructional interventions indicated that children who had gesture-speech mismatches were more receptive to instruction. Thus, researchers concluded that the analysis gestures and speech together are more accurate indicators of thinking and learning than speech alone.

The studies conducted by Roth and colleagues used qualitative analysis from case studies in the context of students learning and communicating topics in science. Researchers indicated that gestures facilitate students' learning as they may communicate abstract science concepts (Roth, 2000). Researchers further provided detailed analysis of the different types of gestures produced when explaining science concepts and the changes in gesture-speech relations. They inferred that, during learning, the types of gestures produced by learners may change from simple pointing gestures to gestures representing abstract information such as movement of electrons (Givry & Roth, 2006; Roth, 2000, 2001; Roth & Lawless, 2002a, b, c). Furthermore, these studies provided evidence that gestures may precede verbal speech, and the delay of speech behind gesture decreases as students are learning.

Little research has been done that uses gestures as a unit of analysis to investigate the ontological categorization of science concepts. In one study, Dreyfus et al. (2015a) advocated a dynamic view of ontology based on the analysis of student and the professor's language, gestures and drawings from two pieces of video data. The first included the analysis of a physics professor's (considered as an expert) explanation of chemical energy in an interdisciplinary science course. The second video analyzed included one of the students in that course responding to a question by the interviewer to explain which graph represented more energy. The predicate analysis of the professor's speech reveals the use of both Energy as a Substance predicates ("release" and "the energy you have to put in") and Energy as a Vertical Location predicates ("drop down to here" and "where they are, at that negative energy") within a single sentence. Similarly, the analysis of student's verbal modality revealed the use of Energy as a Substance ontology and Energy as a Vertical Location. However, the analysis of students' gestures indicates using Energy as a Vertical Location where the student pointed to the vertical axis of the graph. Based on the analysis of data from this study, researchers highlighted the presence of flexibility in students' thinking being evident in the use of multiple ontologies reflected in language, gestures and graph drawings. Yet, Núñez (2015) has criticized Dreyfus et al. (2015a) on their interpretative gesture analysis methodology. Núñez recommended that future researchers use more rigorous methodologies -e.g., systematic gesture analysis- and be more specific on what counts as evidence in research on gesture.

Having said that, the argument between Gupta et al. (2010), Slotta (2011) and Hammer et al. (2011) reveals that a disagreement exists between researchers: some proposing a dynamic while others proposing a more coherent view of ontological categorization. It can be noted that *mostly* language has been used as an analytical lens onto learners and experts' ontological categorization. But also, existing studies have been limited to either qualitative case studies with small sample sizes or quantitative studies recruiting numerous participants without providing in-depth analyses. Some work has begun to use gesture analysis as an analytical lens to investigate learners and experts' ontological categorization of science concepts (Dreyfus et al., 2015a). But this has been limited. Moreover, the commentary provided by Núñez (2015) on Dreyfus et al. (2015a) critiqued the gesture methodology they adopted and recommended future studies adopting a systematic analysis of gestures while providing readers with enough evidence to interpret data differently. Furthermore, the analysis of gesture has not been used as a source of evidence to evaluate the ontological shift and dynamic ontologies views.

Therefore, the current study replicates the study conducted by Slotta et al. (1995) while using both language and gestures as analytical lenses. The study conducted by Slotta et al. has been used as primary reference for more recent studies conducted by proponents of this view such as Slotta and Chi (2006) and Chi et al. (2012). In Slotta et al. (1995), researchers provided students and experts a set of multiple-choice problems about light, heat and electricity where they predicted the outcome of a certain phenomenon followed by verbal explanations of their predictions. Slotta et al. used language as a window onto novices and experts' ontological categorization. Similarly, the current study replicates the study conducted by Slotta et al. (1995) in recruiting participants with different levels of expertise and providing them with a similar set of multiple-choice problems about light, heat and electricity. However, this study used gestures and language as analytical lenses to investigate novices and experts' ontological categorization. Also, the current study balances between quantitative and qualitative methodology by increasing the number of participants recruited as compared to smaller scale qualitative cases studies while providing in-depth analysis of their explanations. The reason for adopting a mixed research methodology is to address the argument between Gupta et al. (2010) and Hammer et al. (2011), on the one hand, and Slotta (2011), on the other. Thus, the evidence provided may be generalizable enough to contribute to settling the disagreement between proponents of the OS theory and proponents of the dynamic view of ontology. Specifically, results provided here aided in determining whether learners and experts categorize science concepts into two distinct categories or have flexibility in their thinking. Also, it helped settle the disagreement between researchers on what instructional strategies are considered effective in overcoming the difficulty students' face in learning and thinking about science.

Purposes of the Study and Research Questions

The current study has three purposes. The first purpose is to examine whether the analysis of gestures (alongside the analysis of speech) can be used as a productive method to identify novices and experts' ontological categorization of science concepts. The second purpose is to identify whether the analysis of gestures and the analysis of speech indicate the same or different ontological categorization of science concepts. The third purpose is to examine the extent to which the categories revealed are stable within individual or change dynamically with context. As such, the study's research questions are:

1. What types of gestures do novices and experts produce while solving physics problems and how do they differ?
2. Do some of the gestures novices and experts produce while formulating science explanations provide evidence of ontological categorization of science concepts?
3. Do speech and gesture analyses reveal the same ontological categorization of concepts in science explanations?

Significance

The study contributes to the literature by overcoming methodological limitations that have not yet been addressed by previous studies using gesture analysis. Also, it provides evidence that addresses the debate between the OS theory and the dynamic view of ontology. Since each theoretical position has different implications for instruction, this study has implications for what instructional approaches are sufficient to overcome the difficulties students face in learning science. The theoretical implications which in turn have pedagogical implications will be discussed in detail in the discussion chapter in light of the results. The following section will discuss the methodological significance of this study

To Methodology. The current study contributes to the field of "conceptual change" by overcoming methodological limitations in the previously conducted studies. Thus, there are two types of methodological significance: extending the previously conducted studies by using gestures and language together as analytical lenses onto ontological categorization; and benefiting from combining qualitative and quantitative methods.

First, the current debate between proponents of the OS theory and dynamic view of ontology reveals language has been used as an analytical lens onto learners and experts' thinking. The predicates used reflects whether learners are categorizing science concepts within the matter or process category. Furthermore, though the study conducted by Dreyfus et al. (2015a) used language and gesture analyses yet, it was critiqued by Núñez (2015) to highlight that their adopted gesture analysis methodology is not sufficient. This suggests that the use of gestures as an analytical lens to uncover learners and experts' categorization of science concepts has been limited. Thus, the evidence provided in this study aided in determining the extent to which gesture analysis is considered as a productive method in identifying the ontological categorizations of novices and experts.

The second type of methodological significance of this study derives from adopting a combined qualitative and quantitative research methodology. The debate existing between Gupta et al. (2010), Slotta (2011) and Hammer et al. (2011) reveals that a disagreement exists between researchers: some proposing a dynamic while others proposing a more coherent view of ontological categorization. On the one hand, Chi and colleagues have argued for the presence of two distinct ontological categories that are not context insensitive. They support their view using a *quantitative* research design where changes in the frequencies in the use of verbal predicates are taken as evidence for changes in categorization (e.g., Slotta et al., 1995). On the other hand, the studies conducted by proponents of the dynamic view of ontology (including the study conducted by Dreyfus et al. (2015a)) were limited to qualitative case studies with small sample sizes where they provided examples of novices and experts invoking multiple categories in everyday language and science learning. This was taken as evidence for a dynamic ontological categorization where novices and experts flexibly invoked multiple ontological categories.

Accordingly, the current study balanced between quantitative and qualitative methods by increasing the sample size while providing detailed examination of learners and experts' problem solving.

CHAPTER II

Review of Literature

In this chapter, the literature motivating this study will be reviewed. The first section introduces an approach to science education research referred to as "conceptual change". This is an area of research that focuses specifically on students' initial conceptual understanding and the changes that take place during instruction. In this section, a number of different theories of conceptual change are reviewed. The disagreement over the degree to which initial student conceptions are coherent will be highlighted. One of the issues that research on conceptual change has addressed is how students (or generally novices) and experts categorize scientific concepts. The second section in this review will elaborate on this aspect of conceptual change, namely, the ontological categorization of concepts by novices and experts and how the shift to expertise occurs. In this section, the issue of how coherent learner conceptions are will be discussed in relation to the specific topic of ontological categorization. Different positions on learner and expert ontological categorization will be reviewed. Specifically, two views will be compared: the ontological shift view, developed by Chi and colleagues; and the dynamic ontological view developed by Gupta, Hammer and others. The review will also highlight that analysis of language has been the main analytical lens to determine learners and experts' ontological categorizations. The third section introduces gesture as another analytical lens onto learners and experts' conceptions and reasoning. The analysis of gesture in research on education and developmental psychology will be reviewed highlighting how gestures are analyzed, what are the kinds of gestures that have been identified and what they can reveal about thinking. The third section will also review research using gesture analysis to examine learners and experts' conceptions, including their ontological categorizations.

This chapter will conclude that the use of gesture as an analytical lens to uncover learner and expert categorization of science concepts has been limited in a number of respects. First, existing studies have been limited to qualitative case studies with small sample sizes. Second, the relationship between conceptions as revealed through gesture and language analysis has not been addressed explicitly. Third, analysis of gesture has not been used as a source of evidence to evaluate the ontological shift and dynamic ontologies views. A concluding section will summarize these limitations of the existing literature and briefly outline the focus of the present study to address these gaps.

Overview of Theories of Conceptual Change

"Conceptual change" is an approach to science education research which focuses specifically on students' initial conceptual understanding and the changes that take place during instruction. Within the field of conceptual change, researchers investigate learning and teaching in science to help understand how naïve understanding is transformed into more scientific understanding. This includes concepts in domains such as Newtonian mechanics, electricity and concepts of matter and density. Efforts by researchers are directed to investigate the nature of students' conceptions and the reason why some misconceptions are robust. Additionally, they study the source of difficulty students face in learning and the instructional strategies deemed sufficient to overcome these difficulties. More specifically, 'change' refers to instruction building on students' prior knowledge and not merely acquiring new knowledge. However, 'concepts' and 'conceptions' are understood differently by different researchers. As such, differences exist among researchers on the degree to which learners' conceptions are considered as organized structures (i.e., coherent) and the degree to which learners respond consistently across different contexts (Amin et al., 2014).

Some theories in the field of conceptual change consider naïve conceptions to be coherent such as the theory-theory view developed by Carey (1986) and McCloskey and Kargon (1988). One of the specific issues addressed by some researchers is ontological categorization. The Ontological Shift (OS) theory, developed by Chi and collogues, has investigated ontological categorization, attributing the most coherence to learners' conceptions. They propose that learners think of science concepts as material substances because they incorrectly categorize these concepts into the matter category (Chi & Slotta, 1993; Chi et al., 1994). Gupta, Hammer and other colleagues (e.g., Gupta et al., 2010; Dreyfus et al., 2014) have also been interested in ontological categorization yet, they have held a different position than that proposed by Chi and colleagues (to be clarified below). Finally, other researchers view naïve conceptions to be fragmented such as the Knowledge in Pieces theory developed by diSessa (1988, 2017) while Vosniadou and colleagues have adopted an intermediate view (e.g., Vosniadou & Brew, 1992; Vosniadou, 2013).

To elaborate, the theory-theory view claims that naïve conceptions are in the form of theories and similar to those of scientists in being coherent and consistent (McCloskey & Kargon, 1988). From this perspective, students' conceptions are formed of core concepts connected to other concepts within a framework (Carey, 1986, 2009). Yet, these naïve conceptions are incompatible with that of scientists. Thus, researchers view the process of conceptual change as a radical *transformation* of naïve conceptual structure into the more scientific one (Amin et al., 2014). It is slow and requires small changes over an extended period of time. From this perspective, learning involves a change in learners' conceptions, beliefs and the relations between them (Wiser & Smith, 2016). Different instructional strategies have been proposed including the use of analogies, use of imagistic representations and thought experiments (Nersessian, 1989).

For example, Wiser (1997) argued that students' naïve theory about heat and temperature is similar to that of scientists in the seventeenth century. Both, students and seventeenth century scientists didn't differentiate between heat and temperature: heat was understood as an intensive quality that is measured using a thermometer where the stronger the heat, the higher the thermometer reading. Also, heat was considered as a force that pushes the thermometer up. In contrast, in modern science heat is extensive as it depends on the mass (e.g., an iceberg has more heat than a hot cup of coffee) while temperature is intensive, measuring the average kinetic energy of a substance. Specifically, Wiser argues that conceptual change in this domain involves a differentiation between heat and temperature. This can be facilitated using computer-based models which highlight the relation between heat and temperature. Additionally, Wiser and Smith (2016) further developed a learning progression curriculum for learning about the atomic molecular theory: It draws a learning trajectory that starts from students' initial conceptions, following intermediate states which includes the changes occurring, and the final state where students' knowledge begins to approximate that of scientists.

While proponents of the theory-theory view identified different changes that learners undergo when learning (one of which was ontological change), proponents of the Ontological Shift (OS) theory have focused in particular on changes in ontological categorization. Proponents of this theory propose that novices incorrectly categorize many science concepts into the matter category instead of the process category, a distinct category that many science concepts belong to (Chi, 2005, 2013; Chi et al., 1994; Henderson et al., 2018; Slotta, 2011). From this perspective, the development of expertise is evident in the use of words and phrases that reflect categorizing science concepts into the process category. For example, saying "heat is gonna go out, escape" indicates thinking of heat as a material substance that *escapes* the walls of the cup. This reveals incorrectly categorizing heat into the matter category. However, saying "heat is a form of energy transfer between hot and cold objects" indicates thinking of heat as a *process* of transfer of energy. Proponents of the OS theory have proposed that instruction should explicitly teach students the properties of the process category and avoid the use of misleading metaphors and analogies as they can reinforce learners' commitment to the matter category (Chi, 2005, 2013; Chi et al., 2012; Slotta & Chi, 2006).

In contrast, diSessa (1988, 1993, 2017) has refuted these views and proposed that naïve conceptions are best viewed as fragmented pieces of knowledge as they are inconsistent and incoherent. He referred to them as phenomenological primitives (p-prims) which are abstract generalizations from physical experiences. diSessa (1988) proposed that p-prims form a network where the connection between them depends on the context. From this perspective, conceptual change is viewed as continuous and instruction should refine students' intuitive conceptions to form more coherent complex systems. An example of a p-prim is Ohm p-prim that students activate when solving physics problems about motion and force, electricity and thermal equilibration (diSessa, 1993, 2017). This p-prim is abstracted from sensorimotor experiences of pulling and pushing objects of different sizes. It interprets the relation between putting more effort and the results obtained: more effort begets more results, and greater resistance begets less result (diSessa, 1988). diSessa (2017) provided an example of a student who productively activated Ohm's p-prim when explaining the rate of temperature change. The student stated: "the liquid likes to be at equilibrium. So, when one is way off, they sort of freak out and work harder to reach equilibrium.… so maybe that's why it moves fast at first, because it's like freaking out."(p. 14). diSessa inferred that the use of "freak out" indicates the activation of Ohm p-prim where liquid is treated as an agent that is affecting the rate of temperature change.

Still, some researchers have adopted an intermediate position between fragmentation and coherence views of knowledge while investigating ontological categorization. This includes the framework theory developed by Vosniadou and colleagues. This view considers naïve conceptions as a coherent, dynamic structure that is formed in the moment to answer a question or solve a problem (Vosniadou, 2013). In line with the Knowledge-in-Pieces theory, the framework theory considers children's intuitive thinking to be formed from everyday experiences. Additionally, framework theory researchers acknowledge that fragmentation is evident as students assimilate scientific information into their existing knowledge. This was evident in the study conducted by Vosniadou and Skopeliti (2017) where some children assimilated the information that the Sun goes down behind the mountains, yet they still held that the Sun moves and goes to another country as the Earth turns around. This is considered a fragmented response where a scientific information is added to learners' naïve conceptions (Vosniadou, 2013). From this perspective, conceptual change is viewed as slow and requires students constructing new ontological categories and representations and learning to shift between them. For example, as students' conceptions about earth is recategorized from earth being a physical object to a physical-astronomical object, they will further understand that the Earth is a spherical, rotating object that appears flat and solid from the perspective of someone living on earth (Vosniadou & Brewer, 1992).

Finally, Gupta, Hammer and others were specifically interested in investigating learners and experts' ontological categorization. They adopted a dynamic view of ontology as they uncovered variability and flexibility in learners and experts' thinking. Unlike what has been proposed by the OS theory, researchers proposed that novices and experts' categorization are dynamic and context-dependent (Dreyfus et al., 2015a; Gupta et al., 2010, Scherr et al., 2012). That is, they suggest that learners and experts move back and forth between categories (Dreyfus et al., 2015a; Gupta et al., 2010). These researchers further highlighted the role of context and the learning environment, emphasizing their effect on learners' thinking and the ontological category invoked in a particular situation. For example, when thinking about energy qualitatively, learners and experts think of energy as a substance (e.g., "leaves blowing in the street *have* energy" reflects thinking of energy being a substance stored/contained in leaves). Yet, when thinking quantitatively about energy while using visual representations (e.g., graphs, energy level diagrams), learners and experts often think of energy as located at a specific location (e.g., "when atoms are pushed, the energy goes *up"* reveals thinking of energy as a location where atoms are located at) (Dreyfus et al., 2014; Scherr et al., 2012).

Ontological Categorization in Conceptual Change

As can be seen in the overview of the literature on conceptual change just presented, there are two distinct lines of research interested in ontological categorization in conceptual change: Ontological Shift (OS) theory developed by Chi and colleagues; and the dynamic ontology view developed by Gupta, Hammer, Dreyfus and other colleagues. Disagreement exists between these two views regarding the nature of students' conceptions, the source of difficulty learners' face in learning and what is considered an effective instructional approach to overcome these difficulties. In this section, these two views and the debate between them are examined in more detail.

Ontological Shift Theory. In the 1990's, Chi and colleagues developed the OS theory of conceptual change (Chi & Slotta 1993; Chi et al., 1994). This theory builds on the work of Keil

(1979) which highlighted the role that ontological categorization plays in concept development in children. He defined ontological knowledge as “one's conception of the basic categories of existence, of what sorts of things there are.” (Keil, 1979, p. 1). That is, it is the set of things that belong to broad categories (e.g., matter and events). Based on the use of predicates which are expressed verbally, Keil proposed a hierarchal representation of ontologies. For example, a cow is an animal, which belongs to the broader category of living things, which in turn belongs to that broad ontological category of matter. However, a football match is a sporting event which belongs to the broader event category. Ontologically different categories are revealed because they differ in the kinds of properties (predicates) that can be attributed to them. Thus, saying “a cow is heavy” [2] or “the baby is heavy” or “the rock is heavy” is appropriate since “is heavy” is a property of material things. Yet, saying “the football match is heavy” or “the party is heavy” doesn’t make sense since “is heavy” is not a property of events. Instead, a football match is characterized by process predicates such as “is an hour long” or “happened yesterday”.

Similarly, Chi and colleagues have drawn on the work of Keil (1979) and proposed that we think of scientific concepts within a hierarchal representation. Figure 1 represents one possible ontological hierarchical representation. The three primary trees are matter, process and mental states. However, researchers have been specifically interested in two trees: matter and process (Chi & Slotta, 1993). The matter tree is composed of two categories: natural kinds and artifacts. The natural kinds category is composed of two subcategories: living thing which is subdivided into plants and animals categories and non-living which is subdivided into solids and liquids categories. The process tree is divided into three categories: procedures, events and

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[2] In this thesis, verbal expressions will be written between quotations: “a cow is an hour long”.

constraint-based interaction categories. Each category is distinguished by a set of predicates (linguistically expressed) which are properties that can be attributed to the category. Chi and colleagues identified some of the matter and process predicates that characterizes the matter category and the process category respectively. For example, ‘move’ is a substance predicate that describes things which belong to the matter category and seen in ontologically acceptable phrases like “the train is moving,” “ice is falling,” or “a man is coming”. That is, coming, falling and moving are all examples of the ‘move’ substance predicate used to characterize objects that belong to the matter category. In contrast, ‘movement’ characterizes a process. For example, saying “wind is the movement of air” reveals thinking of wind as a process (Slotta et al., 1995).

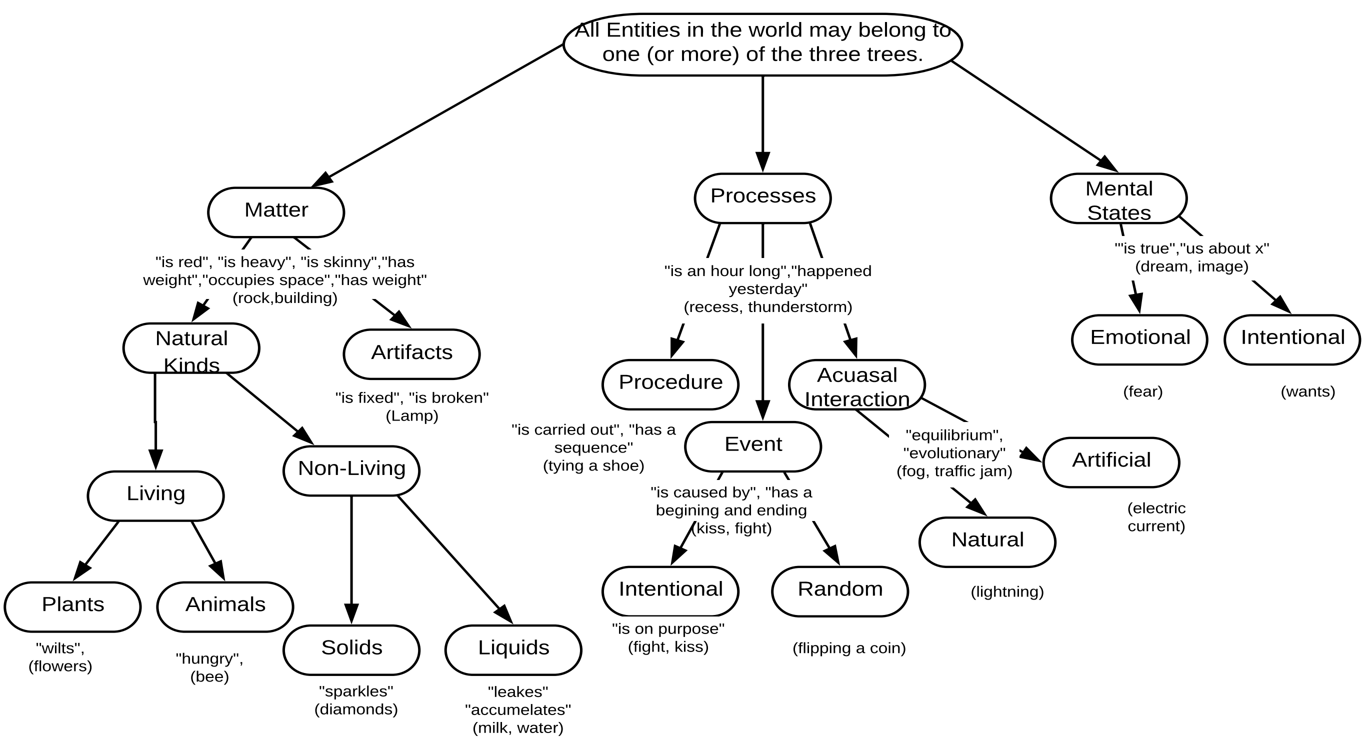

Figure 1: One possible ontological hierarchal representation as proposed by Chi and Slotta (1993). Words or phrases in parenthesis label properties (predicates) that can characterize a member of a particular ontological category.

Based on the synthesis of evidence provided in the literature (see Reiner et al., 2000), Chi et al. (1994) stated that, on the one hand, novices incorrectly categorize science concepts into the matter category[3] while the veridical science concepts belong to another distinct category. More specifically, researchers consider that many science concepts belong to the constraint-based interaction category.[4] In more recent work, researchers referred to the category that science concepts belong to as emergent process in contrast to direct process (Chi, 2005, 2013; Chi et al., 2012). Chi (2005) uses diffusion of blue dye in clear water as an example. That is, the diffusion of blue dye in clear water appears to be *direct* as if the blue dye is flowing or moving in one direction into the clear water. Rather, Chi points out that from a scientific point of view the diffusion of blue dye is a process in which both, the blue dye molecules and water molecules are continuously colliding even after reaching equilibrium. Consequently, diffusion is a complicated *emergent* process thus, belonging to emergent process category.

From this perspective, novices often hold misconceptions as they think of science concepts as a material substance or as a direct process involving a material substance (Chi, 2005). This is revealed in the frequent use of matter predicates instead of process predicates when explaining science concepts like light, heat and electricity which belongs to the distinct process ontological category. Some of the matter predicates that novices use when formulating

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[3] In other work of Chi and colleagues, they have claimed that students' misconceptions come from categorizing concepts to the entities and direct process categories (Chi, 2005) or to sequential processes (Chi 2013; Chi et al., 2012). In this thesis, the focus will be on the matter category because the study involves a replication of an earlier study (Slotta et al., 1995).

[4] In other work of Chi and colleagues (Chi, 2005; Chi 2013; Chi et al., 2012) renamed that target ontological category from constraint-based interaction to emergent process. In this thesis, we will use constraint-based interaction process category.

science explanations are ‘block’, ‘contain’ and ‘move’. The use of these predicates reveals novices have material substance misconceptions. An example of a misconception students often hold is assuming ice *contains* cold that moves into water. This is evident in saying “coldness from the ice flows into water, making the water colder” (Chi, 2013). Chi further elaborated that this kind of language reveals thinking of ice as containing “some ‘cold substance’ like tiny cold molecules … and that this ‘cold substance’ can flow into the surrounding water, which then makes the water colder.” (p. 59). This is evident in using “flows” and “into” which are expressions of aspects of the ‘move’ and ‘contain’ substance predicates, respectively. Another misconception students may hold about heat is reflected in saying “heat can’t get out the cup” or “escapes from the cup”. In these examples, the word “escapes” is an attribute of the ‘move’ substance predicate that characterizes the matter category and the phrase “get out” is an attribute of ‘contain’ substance predicate (Slotta et al., 1995). For example saying that “heat bounces off the walls of cup” reveals thinking of heat as a substance that can be blocked. This is evident in using “bounces” which is an attribute for ‘block’ substance predicate. ‘Block’, ‘contain’ and ‘move’ are all predicates that should be used to describe concepts that belong to the matter category such as water and juice. The frequent use of these predicates is taken as evidence for categorizing heat into the matter category. In contrast, saying that heat is a process in which “heat is exchanged because faster-moving molecules collide with slower-moving molecules, the collisions cause the faster-moving molecules to slow down (thus decreasing their hotness) and the slower-moving molecules to move faster” indicates using ‘excitation’ and ‘movement’ process predicates (Chi, 2013). Thus, the use of these predicates reveals thinking of heat transfer as a process occurring from molecular interactions.

To provide support for this theory, Slotta et al. (1995) conducted a study that aimed to investigate whether novices incorrectly categorize science concepts into the matter category. Accordingly, researchers used language analysis as a window onto novices and experts' ontological categorization since each ontological category is associated with a set of predicates that is expressed linguistically. Participants in this study were of two levels of expertise: nine Grade 9 students were considered novices and two graduate and two Ph.D. university students were considered experts specialized in physics. Participants were provided with 36 multiple-choice problems where they predicted the outcome of a certain phenomenon then they provided verbal explanations of their predictions. These problems were of two types: physics-concept problems and material substance isomorph problems. Half of the provided problems were physics-concept problems and the other half were material substance isomorph problems. The physics concept problems targeted three science concepts: heat, light, and electric current. The material substance isomorph problems had the same structure as the physics concept problems, yet they require a prediction of everyday phenomena involving substances. That is, each physics problem was paired with a material substance isomorph problem. Each physics concept problem in a pair targets a misconception that participants may hold. An example of physics problem and material substance isomorph problem is provided in Figure 2. This example asks whether coffee in a Styrofoam or a ceramic cup will be hotter after 20 minutes. This heat problem specifically aims to investigate whether novices hold a misconception about heat, thinking of it as a substance that can escape, pass, or penetrate some material more easily than others. The paired material substance problem is asking participants to predict which of two helium balloons -one made up of elastic rubber while the other made of paper - would be more buoyant.

Physics-Concept Problem

1. Two cups of hot coffee are poured, one into a styrofoam cup and one into a ceramic mug, and both cups are sealed with airtight lids. What will we find after leaving the two cups sit on a tabletop for twenty minutes?

(N1) a. The coffee in the ceramic mug is hotter than that in the styrofoam cup.
(E) b. The coffee in the styrofoam cup is hotter than that in the ceramic mug.
(N2) c. Neither cup has hotter coffee than the other.
d. Other

Material Substance Isomorph

2. Two different balloons are filled with Helium gas, one made of an ordinary paper bag and one made of durable elastic rubber, and both are sealed tightly at the opening. What will we find after leaving the two balloons floating inside a closet for several hours?

(E.N) a. The balloon made of rubber is more buoyant than the one made of paper.
b. The balloon made of paper is more buoyant than the one made of rubber.
c. Neither balloon is more buoyant than the other.
d. Other

Figure 2*:* Example of physics concept problem and material substance isomorph problem as in Slotta et al. (1995).

Data analysis revealed that when solving material substance problems, the majority of novices and experts' choices were correct. Yet, when solving physics-concept problems, 45% of novices' choices were correct while experts had 100% correct answers. The analysis of novices and experts' predications revealed different patterns: novices most frequently used substance predications in both types of problems. However, experts most frequently used process predicates when explaining physics concept problems. In light of these results, researchers concluded that novices have material substance commitments evident in the *frequent* use of matter predications across time and contexts. From this perspective, context is defined by the different phrases articulated within an explanation or by different tasks performed (Chi et al., 1994). Based on the frequent use of matter predicates by novices and process predicates by experts, proponents of this theory viewed the nature of physics conceptions to be *coherent*. Then, researchers suggested that the development of expertise (i.e., the learning process) requires a reclassification of science concepts from the matter category to the constraint-based process category. For this reason, Chi and colleagues argue that students' misconceptions are robust since: (1) they categorize some science concepts to matter category; and (2) they have to shift their thinking across distinct categories.

Chi and colleagues have proposed different instructional strategies to achieve conceptual change. From their perspective, students' category mistakes should be confronted, and they should be explicitly taught about the correct category (Chi, 2005, 2013). Teachers should help students develop understanding of the targeted category while avoiding the use of metaphors and analogies that might encourage the matter conceptualization. This is done to avoid the assimilation of new knowledge into the matter category (Chi, 2005, 2013; Chi et al., 1993; Chi & Slotta, 1993; Chi et al., 2012; Slotta, 2011). The instructional approach adopted requires students to be aware they need to shift their conceptions from one category to another while teaching them the targeted process category.

To investigate the effectiveness of the proposed instructional strategies, Slotta and Chi (2006) and Chi et al. (2012) designed two modules: concept-general module followed by a concept-specific approach. To assess the effectiveness of the proposed instructional strategy, pre- and posttests were provided to participants. Also, the concept-specific module was provided for both groups while the concept-general module was provided for the experimental group only. The concept-general module aimed to provide training for students about the process ontology using either examples from everyday life (e.g., wolves' hunting as in Chi et al., 2012) or science concepts (e.g., diffusion as in Slotta and Chi, 2006). Participants in these studies were students who had limited knowledge about science concepts or were not majoring in science domains. That is, the study conducted by Slotta and Chi (2006) recruited 24 undergraduate students which were considered as novices, while the study conducted by Chi et al. (2012) was based on Grade 8 and 9 students. In these studies, the analysis of participants' performance in pre- and posttests and the analysis of verbal language (as in Slotta and Chi, 2006) and written language (as in Chi et al., 2012) were indicative of shifting ontological commitments.

The study conducted by Slotta and Chi (2006) investigated the effectiveness of the proposed instructional approach while targeting the science topic electricity. The researchers provided participants with pre- and posttests composed of the same electricity physics-concept problems as in Slotta et al. (1995). Also, the predicate taxonomy developed by Slotta et al. was used to analyze participants' verbal explanations. The concept-general module developed by Slotta and Chi was composed of computer simulations and text that introduced students to the process ontology using air expansion and diffusion as examples. The text discussed that many science concepts belong to the ontological category of constraint-based processes which has special qualities. Also, it included description of these qualities such as the fact that a process has no beginning or an end. This was accompanied by a simulation showing how air molecules are bouncing in a cylinder even after reaching equilibrium. This learning module ended by providing participants with a 25-page text explaining electric current followed by a post-test. The analysis of data revealed the experimental group scored higher than the control in their posttests. Pretest predicate analysis of participants' verbal explanations in the control and experimental groups revealed their reliance on substance predicates in their explanations. However, the analysis of participants' posttest explanations revealed an increase in the process predicates produced by experimental participants while that of control group remained almost unchanged.

Similarly, Chi et al. (2012) adopted the same instructional approach yet targeting the scientific concept of diffusion. Chi et al. provided 8th and 9th grade students with texts that include illustrations and simulations describing information about how ink diffuses in water including the movement of atoms and how they collide. Pre- and posttests were administered to evaluate the effectiveness of their proposed instructional approach. Upon analyzing and comparing data from open-ended questions in posttests of experimental and control participants, researchers indicated that students in experimental group used more process predicates than the control group. The researchers finally concluded that effective instruction should train students in acquiring the process category. Consequently, they recommended that students should be provided with direct instruction about the process ontology to overcome the difficulty they face in learning some science topics. Also, students' existing conceptions should be targeted "indirectly by carefully avoiding any language, analogies, or phenomena that might otherwise reinforce the substance-based view." (Slotta & Chi, 2006).

In sum, the OS theory proposes that novices categorize science concepts into the matter category, which is evident in the predicates they mostly use to talk about scientific concepts in their explanations. From this perspective, *conceptual change* is viewed as an ontological shift from the matter category to the process category. That is, the development of expertise is evident in the frequent use of process predicates when formulating science explanations. Accordingly, instruction should teach students the targeted category while avoiding the use of metaphors and analogies. The success of their instructional strategy is evident as learners frequently used process predicates after instruction.

Dynamic View of Ontology. Gupta, Hammer, Scherr and other researchers are interested in learners and experts' ontological categorization yet, they have adopted a dynamic view of ontology. At a broad level, the dynamic view of knowledge describes students' ideas as a complex system formed of many resources activated differently based on context (Brown & Hammer, 2008). That is, learners possess a wide range of resources which instruction should build on since they are considered to be productive. Specifically, the dynamic view of ontology considers metaphors, which reflect a variety of ontological categories, among these resources that students activate when learning and thinking about science concepts (Dreyfus et al., 2015a; Jeppsson et al., 2013). The activation of these resources is context sensitive and may vary from moment-to-moment (Dreyfus et al., 2015a; Gupta et al., 2010; Jeppsson et al., 2013).

To elaborate, Dreyfus, Scherr and other colleagues have investigated different ontological conceptualizations of energy (i.e., what kind of thing energy is). These studies are grounded on the analysis of science discourse including science textbooks and graphical representations (e.g., graphs and pie charts). In conducting these studies, researchers provide evidence supporting the presence of stability and variability in the ontologies learners and experts invoke when thinking and learning about the topic energy. That is, Scherr et al. (2012) identified three energy ontologies learners and experts invoke. These ontologies reveal variability as energy can be thought of as a substance, as a location, and/or as a stimulus. To arrive at this conclusion, researchers built on the theory of Conceptual Metaphor developed by Lakoff and Johnson (1980).

The Conceptual Metaphor theory proposes that metaphors are pervasive in everyday language. They reveal mapping from a concrete, familiar conceptual domain to the more abstract domain. For example, consider the metaphorical expressions "he *attacked* every weak point in my argument" or "I've never *won* an argument with him". These expressions reveal an implicit metaphor Argument Is a War[5] where argument is an abstract concept construed and talked about as a war. Lakoff and Johnson uncovered many other metaphors that are used in daily life which reflect understanding of abstract concepts such as events, emotions, activities and actions in terms of more concrete ideas such as substances or containers. These are considered ontological metaphors such as States Are Bounded Regions in Space. This conceptual metaphor is implicit in the verbal expressions "I'm *in* love" or "he's *in* a depression". They reveal construing emotional states (e.g., love) as if they are containers. But also, saying "I'm *in* love but we are *going* in *different* directions" reveals thinking of love as a journey. This also indicates that the same abstract concept can be conceptualized using different metaphors. Lakoff and Johnson (1980)

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[5] I will follow the convention used in literature by capitalizing the name of conceptual metaphor such as Time Is Money while metaphorical words within expressions will be in italics such as "you're *wasting* my time".

have argued that metaphors are pervasive, implicit in everyday language and play a role in abstract thinking.

Building on the Conceptual Metaphor theory, the analysis of video recording of a Grade 8 science classroom and physics textbooks by Scherr et al. (2012) revealed three ontological metaphors that are implicit in experts and learners' conversations and physics textbooks: (1) Energy as a Substance which reveals construing energy as a stuff contained in objects (e.g., "leaves blowing in the street *have* energy" reflects thinking of energy as a substance stored/contained in leaves); (2) Energy as a Stimulus reveals construing energy as a forceful entity that has an effect on objects (e.g., "leaves are *pushed* by energy" reflects thinking of energy as a force that is moving the leaves); and (3) Energy as a Vertical Location reveals thinking of energy located at a specific location (e.g., "when atoms are pushed, the energy goes *up"*).

Scherr et al. and Dreyfus et al. (2014) further noted that Energy as a Vertical Location doesn't arise in the context of students thinking of energy qualitatively such as when explaining the blowing of leaves in the street by wind. In this context, learners invoke Energy as a Substance (e.g., "leaves *getting* energy") and Energy as a Stimulus (e.g., "leaves in the street *are pushed* by energy"). However, Energy as a Vertical Location was evident when explaining energy quantitatively. An example of Energy as a Vertical Location is reflected in saying "If the two atoms are apart and form a bond, they *drop down* to *here*" (Dreyfus et al., 2014, p. 5). Using "drop down" and "here" indicates that energy is construed as a location where some object is located. Thus, unlike what had been proposed by Chi and colleagues in the OS theory for the presence of *two distinct* ontological categories that are mutually exclusive, the former evidence reveals the presence of *three* ontological metaphors that are context sensitive (Scherr et al., 2012). When thinking about energy qualitatively, learners and experts invoke the ontological metaphor Energy as a Substance yet, when thinking quantitatively, they often use Energy as a Vertical Location, while Energy as a Stimulus is rarely invoked by experts (Dreyfus et al., 2014; Scherr et al., 2012). Consequently, Scherr et al. assert that the aforementioned ontological metaphors for energy indicate variability in novices and experts' thinking providing support for the dynamic view of ontologies.

Furthermore, the studies conducted by Dreyfus et al. (2014) and Dreyfus et al. (2015a) revealed flexibility in learners and experts' thinking as they use different ontologies when thinking about energy (i.e., they "straddle" ontologies). The studies conducted by Dreyfus and other colleagues is based on the analysis of video recording in an introductory life science course where learners reasoned about negative and positive energy using bar chart representations. The researchers provided examples where students and the professor straddle ontologies. For example, the professor invoked Energy as a Substance and Energy as a Vertical Location ontological metaphors when explaining atomic bonding:

> "If the two atoms are apart and form a bond, they drop down to here and release that much energy. And because that's where they are, at that negative energy, that's equal to the energy you have to put in to get them back apart." (Dreyfus et al., 2014, p. 5)

The predicate analysis of the professor's speech reveals using both Energy as a Substance predicates ("release" and "the energy you have to put in") and Energy as a Vertical Location predicates ("drop down to here" and "where they are, at that negative energy") within a single sentence. Also, Dreyfus et al (2015a) provided an example of a student (Betsy) who straddled ontologies when explaining which graph represented more energy in a follow-up interview:

> "So if I put these two graphs together, so this is ATP and it takes a little bit of energy to put in to get ADP, but ADP is much more stable than this, and this is because the phosphate reacts with the water and forms a really stable. So it's in a well but it falls into a deeper well once the bond breaks. I'm pretty sure." (p. 830)

This example reveals flexibility in the learner's thinking reflected in using Energy as a Substance predicates ("energy to put in") and Energy as a Vertical Location ontological metaphors ("in a well" and "falls into a deeper well").

Based on these analyses, researchers advocating for a dynamic view of ontology have argued that learners and experts don't categorize science concepts into one category, as has been proposed by Chi and colleagues (Gupta et al., 2010). Rather, researchers proposing a dynamic view of ontology have emphasized the presence of flexibility in novices and experts' thinking evident in their drawing on multiple ontologies within a sentence. Such flexibility is revealed in the use of multiple metaphors, evident in the language used by famous scientists.

The study conducted by Amin (2009) analyzed the term *energy* in *The Feynman Lectures on Physics* textbook which is representative of the scientific understanding of the concept of energy. The analysis of Feynman's use of the term energy reveals extensive use of metaphors when explaining three aspects of the concept of energy: transformation, conservation and transport/exchange. Fifteen different conceptual metaphors were identified among which were the three ontological metaphors that have been identified by Scherr et al. (2012): Energy as a Substance, Location Event Structure Metaphor, and Energy as a Stimulus. For instance, when explaining energy exchange, the Object Event Structure metaphor appears where energy is referred to as an object that is *possessed* or *contained*. This is revealed in the metaphorical expressions: "the energy an object *has"*, "it *gains* or *losses* energy" and "energy will be *given* to some material". In contrast, when explaining energy transformation, forms of energy are referred to as containers and the transformation of energy as moving in and out the containers. The Location Event Structure conceptual metaphor was evident in the metaphorical expressions: "to illustrate the existence of energy *in* other forms" and "the elastic energy is converted to kinetic energy and it goes *back* and *forth"*. Finally, in explaining energy conservation, different conceptual metaphors were used to explain energy as a quantity conserved regardless of the changes occurring at the macroscopic level. Some of these metaphors include referring to energy as an object that has an amount (e.g., Q is the *amount of* heat energy added to") and as an object that moves on a vertical scale (e.g., energy *goes up*). From this perspective, abstract science concepts are understood using multiple metaphors. These metaphorical construals are clearly implicit since Feynman has explicitly insisted that energy is an abstract concept:

> There is a fact, or if you wish, a law, governing all natural phenomena that are known to date…The law is called the conservation of energy. It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens. It is not a description of a mechanism, or anything concrete;" (Feynman et al., 1965, p. 124)

The use of metaphors by expert physicists, as reviewed above, has been taken as evidence to argue against the OS theory in which novices are claimed to be *incorrectly thinking* of science concepts as a material substance. Since Feynman, an expert physicist, entertains a material substance conceptualization of science concepts, this suggests that the development of expertise can't simply be viewed as using process predicates instead of matter predicates as has been proposed.

The use of multiple metaphors by expert physicists and in science discourse provides support for proponents of the dynamic view of ontology to advocate instructional strategies different than that proposed by the OS theory. Specifically, researchers have raised pedagogical advantages for the use of multiple ontologies in instruction (Dreyfus et al., 2014; Dreyfus et al. 2015a; Scherr et al., 2012). Having identified three ontological metaphors of energy, Scherr et al. (2012) further elaborated that each ontology captures an important aspect of the energy concept that is not captured by the others. The use of Energy as a Substance ontological metaphor captures some features of the veridical science concept: energy is conserved, localized (i.e., has a spatial location), transferred among objects and accumulated in objects, located in objects (i.e., construed as containers of energy), and changes in form (Close & Scherr, 2015; Scherr et al., 2012). Likewise, Energy as a Vertical Location captures important aspects of the canonical energy concept that the substance metaphor doesn't: "energy can be positive or negative; changes in potential energy are more physically meaningful than the actual value of potential energy" (Dreyfus et al., 2014, p. 4). Also, Scherr et al. noted that Energy as a Stimulus reasserts the idea that energy is associated with the ability to do work and provides the basis for causal explanations of physical process. This is used only rarely by experts when thinking about energy. The preceding discussion reveals that, unlike what was proposed by the OS theory, researchers advocating for this view recommended that instruction should not focus on a single ontological category. Rather, it should provide students the opportunity to use multiple ontological metaphors reflected in speech and graphical representations where they learn to coordinate between these ontologies as experts do.

Researchers have emphasized the advantages of using multiple ontological metaphors in instruction yet, they have noted some limitations of the Energy as a Substance ontological metaphor. That is, material substance understandings are at odds with the nature of energy as an abstract concept as defined by Feynman et al. (1965). This is the case since energy is an abstract idea that represents mathematical quantity and not a concrete substance (Feynman et al., 1965). It is "invisible, massless, permeates objects, it occurs in various forms, and it transfers and transforms in the course of physical process" (Scherr et al., 2012, p. 6). Thus, energy can't be characterized as a substance by being pushable, frictional or affected by gravity. However, Scherr et al. noted that learners can productively attribute *some* material substance characteristics to the energy concept by being conservable, containable, additive, movable and transferred. This suggests that learners think of energy as a quasi-material as proposed by Duit (1987). However, this thinking can limit understanding of how energy can be transferred into different forms. Duit (1987) and Scherr et al. (2012) asserted that even with the presence of some limitations, quasi-material understanding of energy facilitates students' learning by concretizing abstract concepts and making it more connected to their everyday life experiences.

The preceding discussion indicates the presence of different ontologies which are used in a context sensitive manner by learners and experts. From this perspective, everyday language and scientific language is rich in metaphorical expressions. On the one hand, science concepts (e.g., energy) are abstract, mathematical quantities and may be best understood as a process (e.g., heat). In contrast, the use of metaphors reveals thinking of energy as a substance-like entity. Thus, the distinction between the nature of science concepts and the metaphorical expressions used to explain and understand these concepts result in an ontological mismatch. These findings suggest that language is used in more complex ways than it had been proposed by proponents of OS theory. This raises the questions: How can instructional strategies avoid the use of metaphors if metaphorical expressions are pervasive in lay and scientific language? The pervasiveness of metaphors in scientific and lay language conflicts with the suppositions of the OS theory. Chi and colleagues who have claimed that the use of matter predicates such as *flows*, *leaves*, or *goes* reveal that students are categorizing a concept incorrectly to the matter category. From the perspective of CM theory, the use of matter predicates are metaphors and provides evidence that students are structuring and constructing their knowledge from both lay and scientific discourse which reveals continuity in learning (Amin, 2009). In line with that, the dynamic view of ontology has pedagogical implications that contrasts with the pedagogical approach proposed by the OS theory.

As proponents of the dynamic view of ontology highlighted the advantages of invoking multiple ontological metaphors, they further emphasized the importance of providing learners with an effective learning environment that engages useful resources. This includes using different visual representations. The proposed pedagogical implications are based on the studies conducted by Dreyfus, Scherr and colleagues revealing ontological metaphors are context sensitive. For instance, describing energy as a stimulus that causes a change (which reflects invoking Energy as a Stimulus metaphor) in the context of explaining energy conservation doesn't support distinguishing between force and energy. Yet, this metaphor is productive when teaching students about work and changes in energy (Daane et al., 2018). In a similar vein, in the context of explaining chemical bonding and energy changes associated with chemical bonding, invoking Energy as a Vertical Location by using graphical representations will support understanding negative energy (Dreyfus et al., 2014; Scherr et al., 2012).

On that basis, Scherr and colleagues developed the Energy Project: a professional development project conducted for science teachers. This project advocates a substance metaphor of energy through the Energy Theater activity (Close &Scherr, 2015; Daane et al., 2018; Scherr et al., 2012). The activity builds on a concrete learning environment where teachers act as learners and use different representations (including objects such as ropes and the human body itself) to understand energy transfer and transformation in specific scenarios such as cooling food in a refrigerator (Close & Scherr, 2015; Daane et al., 2018; Scherr et al., 2013). Participants in this activity act as units of energy that have one form at a specific time. Yet, the objects they use (e.g., loops of rope) represent an aspect in their scenario, such as the outer surface of a bulb as in Scherr et al. (2013), or a pully and a man, as in Close and Scherr (2015). That is, each teacher embodies a unit of energy where she/he moves from one region to another on the floor to represent how energy is transferred. Also, specific changes in hand signs reflect changes in energy form while the number of teachers in a specific region represents the quantity of energy. Consequently, these representations embody the Energy as a Substance ontological metaphor. The success of this project is determined as teachers develop deep understanding of how to conserve energy while tracking how energy is transformed and transferred within a system. Recently, Daane et al. (2018) added that the success of this project is evident as teachers were able to identify metaphors used by students to understand energy as an abstract concept.

Ontological Shift vs. Dynamic Ontologies View. Given the preceding discussion, a disagreement exists among researchers where language has been used as an analytical lens. Gupta et al. (2010) critiqued the OS theory with regard to the claims that (1) novices possess a material substance ontological commitment that is constraining their understanding and which is revealed in the use of matter predicates; (2) experts think of science concepts within the process ontology as reflected in the predicates they produce; and (3) the ontological categories invoked by novices and experts are context-independent. Gupta et al. developed their critique of these claims based on two sources: evidence provided by Lakoff and Johnson (1980) on the use of multiple metaphors to conceptualize abstract concepts in everyday language and evidence from the science education literature.

In building their argument, Gupta et al. (2010) drew on the Conceptual Metaphor theory developed by Lakoff and Johnson (1980) which indicates that metaphors implicit in everyday language cross ontological categories (e.g., saying that “the party was *massive*” reveals using Events Are Objects conceptual metaphor where a party, which is strictly an event is characterized as massive, a property of material objects). Gupta et al. proceeded to argue by drawing on previous research among which was the studies conducted by Chi and colleagues which reveal metaphors are pervasive in scientific language. Furthermore, to support their argument, researchers provided evidence from a qualitative case study where both novices and experts productively and flexibly invoke multiple ontologies depending on the context. Specifically, Dreyfus et al. (2015a) argued that acquiring expertise in physics involves learning to flexibly coordinate metaphors and ontological categories in different contexts. Consequently, researchers. argued in favor of a *dynamic view of ontology* instead of the *static view* of ontology as proposed by Chi and colleagues. Finally, the researchers further raised a methodological concern with the approach taken by Chi and colleagues. That is, they argued that Chi and colleagues' framework limited their interpretation of the data.

In response to that, Slotta (2011) argued that because "no empirical study has yet been performed, it is not possible to make any strong connection between Chi's position and the notions of flexibility described by Gupta et al." (p. 159). Instead, Slotta argued for the presence of *parallel* ontological categorizations that are context-insensitive. That is, experts often use substance-like and process predicates with awareness when to use substance-like predicates and when not to (Slotta, 2011; Slotta & Chi, 2006). Specifically, Henderson et al. (2017) stated: "Experts may indeed use expressions that suggest an ontological miscategorization, but do so with full awareness that their usage of terms and predicates do not align ontologically (e.g., for instructional purposes)." (p. 30). Slotta emphasized the evidence provided in the study conducted by Slotta and Chi (2006) reveals (with the development of expertise) flexibility in the use of multiple attributes. Thus, Slotta (2011) stated "it is unclear how Chi's notion of parallel ontologies is different from the "flexible ontology" proposed by Gupta et al." (p. 157). He further concluded that the examples and discussion provided by Gupta et al. neither explain their view of flexible ontologies nor does it explain the reason for robustness in learners' misconceptions. Rather, Slotta suggested that the examples provided by Gupta et al. documents instances where novices and experts switch ontological *attributes*.

In response to Slotta (2011), Hammer et al. (2011) refuted Slotta's claim that Gupta et al. (2010) didn't provide evidence of novices and experts straddling categories. They pointed out that Slotta didn't consider the evidence from their *case study* as evidence. Hammer et al. (2011) reasserted their position that language can't be viewed simply as a window into static ontologies which "have the form of discrete categories in the mind, as fixed structures that constrain reasoning." (p. 164). Hammer et al. drew on the general dynamic view of knowledge and thinking as discussed by previous researchers (e.g., Brown and Hammer, 2008; Siegler, 1998) in explaining novices' thinking of science concepts as material substances. At the broad level, the dynamic view considers novices and experts possessing a wide range of resources that can be activated selectively based on specific conditions and situations (Brown & Hammer, 2008). From this perspective, stability is not seen as a *fixed unitary category.* Rather, it is evident in the consistency of students' reasoning. Hammer et al. concluded by highlighting divergence in the adopted research methodologies. On the one hand, Gupta et al. used evidence from a qualitative case study conducted in naturalistic contexts specifically, providing evidence of a student (Kimberly) who was able to reach the correct physicist conceptualization using matter and process ontologies. In contrast, Chi and colleagues grounded their argument on quantitative experimental studies were evidence from aggregated data across many participants is taken as evidence for a static ontological categorization. Following that, Hammer et al. concluded by emphasizing the evidence presented by Gupta et al. further reveals that instruction can't simply avoid the use of material ontology (i.e. avoid the use of metaphors and analogies).

This debate reveals that researchers have not yet reached consensus whether students' ontological categorization of science concepts is *static,* as has been proposed by Chi and colleagues, or *dynamic,* as has been proposed by proponents of the dynamic view of ontology. This disagreement is important to try to resolve because it influences which instructional approach is likely to be more effective in overcoming difficulties learners face when learning. The following section will highlight another line of research where gestures have been used as a lens onto thinking and learning. Having gestures as an analytical lens might offer a source of additional data to contribute to this debate and help evaluate the two alternative theoretical positions.

Gestures as an Analytical Lens

Gestures have been studied by a variety of people for different purposes and using different methodologies. Most of the literature on gestures has investigated how gestures are used in communication. Additionally, they have studied the types of gestures produced in everyday contexts such as expressing scenes from a cartoon movie after watching it (e.g., McNeill, 1985, 1992), or discussing morality (e.g., Cienki and Müller, 2008; Cienki, 2017). Another line of studies has investigated the gestures produced when solving Piagetian tasks (Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986; Perry et al., 1988) and when learning science in naturalistic contexts (e.g., Roth and Lawless, 2002a; Crowder, 1996a). Upon analyzing the gestures produced, researchers have identified changes in the use of gestures and their relation to speech as they accompany learning. Some identified these changes as changes in the physical form of gestures (e.g., Scherr, 2008) or as changes in the relation between gestures and articulated speech (Crowder, 1996a, b; Goldin-Meadow, 2003; Roth & Lawless, 2002b). When investigating these changes, researchers have identified shifts in students' talk or state of ideas (e.g., Crowder, 1996a, b; Scherr, 2008). More specifically, and particularly relevant to the study proposed here, some researchers have been interested in analyzing gestures to provide evidence that learners and experts straddle ontological categories thus, advocating for a dynamic view of ontology (e.g., Dreyfus et al., 2015a).

The following section will first highlight what are the kinds of gestures that have been identified. This section will define what is considered as gesturing and the types of gestures produced. The following sections will highlight how gestures were analyzed and what they may reveal about thinking and learning.

Definition of Gestures. McNeill (1992) defined gestures as "spontaneous movements of the arms and hands and are closely synchronized with the flow of speech" (p. 11). More recently, Novack and Goldin-Meadow (2017) considered gestures as representational actions: they are representational as they "represent something other than themselves and they are *actions* [emphasis in original] in that they involve movements of the body" (p. 653). In this sense, the manipulation of objects is not considered as gesturing. For example, opening a jar is not considered a gesture. However, producing a twisting gesture near the jar is considered gesturing as it communicates and represents information to a speaker such as teaching how to open a jar (Novack & Goldin-Meadow, 2017).

McNeill (1985, 1992) considered gestures as a window onto thoughts and argued that gestures and language form a single integrated system. For example, saying "I ran all the way up" while gesturing a spiral movement reveals a description of a person climbing a spiral staircase (Congdon et al., 2018; Novack & Goldin-Meadow, 2017). Without the spiral gesturing, it would not be clear whether the staircase is spiral or straight. But also, without the speech it would not be clear whether someone is talking about mounting a staircase or about the uncontrolled change in prices (Congdon et al., 2018; Novack & Goldin-Meadow, 2017). This reveals that gesture and speech are complementary as they provide a complete picture of the speaker's thoughts (McNeill, 1992). This example further reveals that the meaning attributed to the gesture emerges from its physical form (Goldin-Meadow, 2003). The spiral movement reveals mounting a spiral staircase while a straight ascending gesture reveal mounting a straight staircase. Furthermore, the meaning conveyed by gestures emerges from the context they are produced in (Goldin-Meadow, 2003; Kendon, 2005). For example, gesturing as if holding an object between the hands while saying "it was a Sylvester and Tweety cartoon" indicates the participant was expressing the cartoon genre (Sylvester and Tweety) as if bounded and contained between his hands in the study conducted by McNeill (1992). The same gesture was used by a university professor in the study conducted by Dreyfus et al. (2015a) where the professor was referring to Lennard-Jones potential well in a chemistry lecture. Also, the study conducted by Dreyfus et al. (2015b) documented a similar gesture by a student who held his hand in the shape of holding an object when explaining a physics problem about a ball that can be motionless and have zero kinetic energy.

Types of Gestures. The studies conducted by McNeill (1992) analyzed the gestures produced by participants when narrating a cartoon film. He classified gestures that co-occur with speech into four types: iconic, metaphoric, deictic, and beat. McNeill was not interested in emblems, which are conventionalized gestures such as gesturing thumbs-up for "OK". This is the case since they don't display images, are not accompanied by speech and are produced by people who are fully aware they are using them.

McNeill (1985) has defined beats as “a simple and rapid hand movement of a type that usually accompanies words whose importance depends on multi-sentence text relations” (p. 345). McNeill (1992) illustrates beat gestures with the gesture of two-hand movement phases such as hand flick or moving hands up and down. This type of gesture doesn’t present meaningful content itself (McNeill, 1985, 1992; Novack & Goldin-Meadow, 2017). Rather, it is used by the speaker to highlight a word of a phrase in the speech he/she feels important. Also, this gesture may be superimposed on iconic, metaphoric, or deictic gestures. An example of a beat gesture would be producing a vertical downward movement with the palm directed to the side while saying “take a decision”. The beat gesture is produced while articulating “decision” to emphasize on it.

Both iconic and metaphoric gestures reveal meanings similar to that depicted in language. However, an iconic gesture “is one that in form and manner of execution exhibits a meaning relevant to the simultaneously expressed linguistic meaning. Iconic gestures have a formal relation to the semantic content of the linguistic unit.” (McNeill, 1985, p. 354). An example of an iconic gesture would be bending the hand in an arc movement when saying “he bends it way back” to explain how a character in the comic book bends a tree. The movement of the hand depicts the image of bending a tree. In contrast, metaphoric gestures have indirect linguistic meaning by presenting a concrete image of an abstract concept (McNeill, 1992). That is, McNeill (1985) considered them as “semantically parallel to sentences with abstract meanings.” (p. 356). He provided various examples of conduit gestures that reveal conduit metaphors building on the Conceptual Metaphor theory. Lakoff and Johnson (1980) defined conduit metaphors as instances where “the speaker puts ideas (objects) into words (containers) and sends them (along a conduit) to a hearer who takes the idea/objects out of the word/containers” (p. 10). An example of verbal expression of a conduit metaphor is saying “I *gave* you that idea.”. This expression reveals construing “ideas” as an object that is *given* to the hearer. For example, producing a beckoning gesture with both hands in the context of saying “tell me what you have in mind” is considered a metaphoric gesture. This is the case since the speaker is requesting from the hearer to *give* her/him the *idea*. That is, the idea is construed as an object. More example about metaphoric gestures was provided by McNeill (1992) evident when saying “it was a Sylvester and Tweety cartoon”. In this context, the participant’s hands rise up parallel to each other as if holding an object between his hands. McNeill considered this gesture to be expressing the cartoon genre which is an abstract notion. In another work, McNeill (2005) stated that this gesture has an iconic component since “the form of the gesture resembles holding an object” (p. 39). Also, it has a metaphoric component since it depicts an *abstract* object (i.e., cartoon genre) is being held or presented between the hands. Accordingly, McNeill (1992, 2005) classified this gesture as a metaphorical one.

Finally, deictic gestures are “pointing movements, which are prototypically performed with the pointing finger, although any extensible body part or object can be used, including the head, nose, or chin, as well as manipulated artifacts” (McNeill, 1992, p. 80). The pointing can refer to concrete objects or to an abstract concept. For example, pointing to the space between the talker and listener while saying “where did you come from before?” is considered as abstract pointing. Based on the established conversation, McNeill mentioned that the abstract pointing gesture was referring to the physical location of a city. Yet, pointing to the south hemisphere on the globe model when saying “it is winter in the south” is considered as concrete pointing since it is referring to the location of the south hemisphere on the globe model (Crowder, 1996a).

Cienki (2008, 2010, 2016) criticized the classification provided by McNeill (1985, 1992) to propose that the classification of gestures is more complex than had been proposed. While McNeill differentiated between iconic and metaphorical gestures, Cienki argued that this differentiation is more complex since talking about abstract concepts doesn't imply that the co-occurring gesture is a metaphorical gesture. Also, depending on the contextual topic, some gestures (e.g., emblems and beats) may reveal metaphors. To elaborate, Cienki provided an example where in explaining geometry, one might represent a triangle using two hands. In this context, though the speech was abstract, the gesture is considered iconic as it depicts the image of a triangle. Following this, Cienki proposed that depending on the context, gestures might represent information in an iconic form, yet this representation may be metaphoric.

Cienki further added that beats and emblems might convey metaphors. For example, the use of the "thumb-up" emblem gesture conveys the meaning that good ideas are located up while bad ideas are located down. Following the work of Lakoff and Johnson (1980), Cienki (2008) mentioned that the use of this gesture reveals the Orientation Metaphor: Good Is Up; Bad Is Down. Thus, Cienki proposed that emblems might function as metaphorical gestures. Additionally, he proposed that even beats might convey metaphors that can't be expressed in speech. For example, when a speaker was metaphorically talking about morality as being either black or white, she made a chopping gesture with her right hand against the palm of her left hand. Accordingly, the former gesture reveals a spatial metaphor that made a clear distinction between two moral behaviors, right and wrong. Cienki (2008) suggested that this metaphor was depicted in the gesture modality since it couldn't be verbally expressed. During which, the verbal expression revealed distinction between two moral behavior using color metaphor since it couldn't be expressed using gestures.

As such, Cienki (2008) argued that coding and analyzing gestures can't be reduced to a procedure that differentiate whether a gesture is metaphoric or not. Rather, Cienki (2010, 2016) proposed, based on the context of speech, gestures may be classified based on their referential functions into concrete referential gestures and abstract referential gestures. Concrete referential gestures are gestures that iconically represent some features of the speech such as motion of an object, shape of an object or even a pointing gesture referring to concrete object which may not be seen in the moment. However, abstract referential gestures are gestures that are referring to an abstract concept via their motion and their physical form. Following that, Cienki have supported the analysis of metaphoric gestures by the work of Lakoff and Johnson (1980) and Johnson (1987) in the Conceptual Metaphor theory. The topic of gesture classification will be reviewed in the following sections.

Research on Gestures

Gesture analysis has been used by various researchers as an analytical lens to investigate learners' thinking. When using gestures as an analytical lens, researchers inferred that gestures may convey information that is abstract, not accessible yet in speech, and/or different than that articulated. Additionally, when learning and while being provided with instruction, researchers identified changes in the gestures produced and their relation to speech. This includes changes in three dimensions: the physical form of the gestures produced, the types of gestures produced, and the relation between the gesture's produced and its corresponding speech. More specifically, and particularly relevant to the study proposed here, some researchers have been interested in analyzing gestures to provide evidence that learners and experts straddle ontological categories thus, advocating for a dynamic view of ontology (e.g., Dreyfus et al., 2015a). The following sections will further discuss these notions in the light of the studies conducted by different researchers.

Gestures as a Window onto Thought. The studies conducted by various researchers reveal that gestures may convey information that is not articulated (see Goldin-Meadow, 2003 and Roth, 2000). But also, this information may be abstract. To elaborate, Roth and colleagues were interested in investigating the gestures produced by students as they were learning science over an extended period of time (two or four months). One of the particular interests for researchers was investigating students' gestures and the emergence of science explanations. One of the examples provided by Roth (2000) and Roth and Lawless (2002b) was of a Grade 8 student (Gaalen) who was using computer-based Newtonian microworlds about force and velocity. During which, the student pointed to an arrow on the screen while saying *"*try to put it upwards*"*. His gesture was accompanied with the indexical term "it". The researchers identified this gesture as deictic that was referring to an abstract concept which was force. Thus, they inferred that the use of deictic gesture and indexical term facilitated the communication of the abstract concept to his peers especially as the student hadn't learnt the scientific term yet (Roth, 2000; Roth & Lawless, 2002c).

Furthermore, researchers provided another example where they inferred that metaphoric gestures may convey abstract information not articulated in speech. For example, one of the students (Matt) when investigating the electrostatic influence of a charged plastic ruler approaching a steel rod on the metal pith ball, he produced metaphorical and deictic gestures. That is, the student pointed to the end of the rod and moved his hand along it. While gesturing the student articulated "he is holding it to here, all the electrons disappear into this part because the electrons repel each other. And now because there, here is an electron surplus". Roth (2000) considered this gesture to convey the movement of electrons at the microscopic level: from the charged plastic ruler to the steering rod to the metal pith ball thus, causing the ball to bounce at the macroscopic level. Accordingly, Givry and Roth (2006) perceived gestures link different layers of content: macroscopic and microscopic. But also, researchers highlighted that iconic and metaphoric gestures have topological feature (i.e., spatial characteristic). This specific feature facilitates the communication of abstract concepts which are difficult to describe in the verbal modality (e.g., movement of electrons) (Givry & Roth, 2006; Roth, 2000, 2001; Roth & Lawless, 2002a, b, c). The preceding examples reveal that when using gestures (whether deictic, iconic, and/ or metaphoric) as an analytical lens onto thinking, they convey information that is abstract and not articulated in speech. Interestingly, different studies were conducted by Goldin-Meadow and colleagues which revealed that gestures may convey information that is different than that articulated.

Goldin-Meadow and colleagues analyzed children's gestures and speech in the context of solving problems such as math equivalence (e.g., Perry et al., 1988; Alibali & Goldin-Meadow, 1993) and Piagetian conversation (e.g., Church and Goldin-Meadow, 1986). Researchers analyzed the gestures produced by children ranging between five to eleven year old (Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986; Perry et al., 1988). The analysis of data collected from various studies reveal that gestures may convey information *different* than that found in speech (Congdon et al., 2018; Goldin-Meadow, 2003). The term mismatch/discordance has been used when "gesture and speech convey different information" (Goldin-Meadow, 2003, p. 26). An example of a gesture-speech mismatch was when a child explained that the amount of water in the two containers was different as one of them is lower than the other. While saying so, the child gestured a C-handshape. This indicate that the child's gesture was referring to the width of the container while the speech was referring to the height of the container (Church & Goldin-Meadow, 1986).

Moreover, the analysis of results from these studies revealed that almost all students gestured, and gesture-speech mismatch is not limited to a particular concept. These inferences were supported by having 27 out of 28 children produce gestures when explaining Piagetian conservation task in Study 1 conducted by Church and Goldin-Meadow (1986); and 30 out of 37 students producing gestures when explaining math equivalence problems in Study 1 conducted by Perry et al. (1988). Researchers considered a child as discordant if he/she had at least three out of six explanations where the gesture doesn't match that of speech. Following this criteria, Church and Goldin-Meadow indicated that 13 out of 28 children were discordant in the conversation task. Notable, Study 2 conducted by Perry et al. revealed that discordant state is not content-specific as six out of the nine children who were discordant in math equivalence were actually concordant in conversation task.

Thus, one may infer that the analysis of gestures is more accurate indicator about thinking than speech alone (Congdon et al., 2018; Goldin-Meadow, 2003). This notion was further supported by the study conducted by Crowder (1996a, b) and Close and Scherr (2012). These studies highlight that having gestures as an analytical lens helps in identifying two language activities as revealed by Crowder. But also, they help in identifying different levels of expertise as revealed by Close and Scherr.

In elaboration of the above, Crowder (1996a, b) was interested in investigating whether gestures distinguish between two language activities (descriptive and explanatory). To do so, Crowder analyzed the patterns of the produced gestures and co-occurring speech based on McNeill's gesture classification. The analysis of the results revealed that specific gestures were associated with descriptive talk and explanatory talk. For instance, redundant, iconic gestures and deictic gestures were associated with descriptive talk. They were either timed with speech or are delayed beyond words. However, explanatory talk was associated with enhancing iconic gestures -i.e., enhance and elaborate- and beats that proceed talk. As students were shifting from one type of talk to another, researchers indicated that some of the beats produced signaled this shift. Based on the different patterns of gesture-speech coordination, Crowder inferred that the analysis of gestures aided in distinguishing between explanatory science talk and descriptive talk.

Furthermore, the article provided by Close and Scherr (2012) revealed that the analysis of gestures (alongside speech) aids in identifying different levels of expertise. The researchers were specifically interested in analyzing gestures to further understand knowledge development and learning. The data analyzed in this article was from a previous video recording of teachers (Donna, Mark and Beth) learning in a summer course about energy transfer in refrigerators. The researchers identified three gestures produced by participants: (1) fist; (2) bracket where the fingers bend perpendicular to the palm; and (3) cap where the fingers form a C-handshape. The analysis revealed that two learners (Donna and Mark) were considered experts because they differentiated between phase change (from liquid to gas or gas to liquid) and the change in the distance between atoms and their vibration. However, Beth was considered as a novice since she didn't differentiate between these two concepts. The analysis of language, gestures and their relation revealed that this differentiation was reflected in both gestural and verbal modalities.

Close and Scherr (2012) provided different examples in elaboration of that notion. For example, the analysis of Dona and Mark's discussion indicates distinguishing between these two concepts in, both, verbal and gestural modalities. This was evident in saying "moved farther apart", "faster", and "changing position". Additionally, this differentiation was evident in the gestural modality where the gestures produced by Mark and Donna indicate distinguishing between the motion of molecules and distance. This is the case since Mark and Donna produced a fist and bracket gestures. For example, the fist gesture was produced when articulating "molecules moving faster". Accordingly, researchers proposed that this gesture depicts the movement of molecules as Mark and Donna moved their fists in a back and forth movement. Also, the bracket gesture was produced when articulating "moved farther apart". Thus, it depicts the change in the space between molecules as the hands bounced laterally outwards. For example, Mark said "they're moved apart but the molecules aren't moving faster." while bouncing his hands outwards in a bracket shape when articulating the word "apart". Close and Scherr (2012) considered this gesture is referring to the change in the space between molecules. However, the gestures produced by Beth didn't reveal differentiation between the movement of molecules and the change in the distance between gas molecules compared to liquid. For example, while Beth was saying "when you're changing phase, you're making the molecules move either way more", she produced only capping gestures. That is, Beth held her hands in a C-handshape and expanded her gesture to the size of her body. Accordingly, researchers proposed that this gesture and the hands movement doesn't indicate differentiation between motion and distance between molecules. Thus, one may infer that the analysis of gestures (alongside speech) helped in identifying different levels of expertise.

In line of the above, gestures may be considered as a productive method onto learners and experts thinking than speech alone. Specifically, they may reveal information that is abstract and/or different than that conveyed in speech. They also aid in identifying two types of language activities as evident in the study conducted by Crowder (1996a, b). Additionally, gesture analysis helped researchers in understanding novices and experts' conceptual development as discussed by Close and Scherr (2012). Having said that, we find the analysis of gestures is interesting to further understand learners' thinking as they are engaged in the learning process. Thus, we are posing the question: how is the use of gestures changing with the change in learner's thinking?

Changes in the Gestures Produced and their Relation to Speech. Different researchers have revealed, when using gestures as an analytical lens, changes in the use of gestures accompanying learning. They provided evidence showing that as students are learning, there are changes in three dimensions: the gestures produced and their relation to speech, the types of the gestures produced, and the physical form of the gestures. The following sections will elaborate on these notions.

Scherr (2008) stated that the analysis of gestures can "offer one source of evidence of students' engagement in constructive thinking" (p. 4). Goldin-Meadow (2003) further added that they are more accurate indicator onto *learning* than speech alone. This inference was based on the analysis of children solving tasks then they are provided with instruction. The analysis of these studies revealed, upon providing children with instruction, those who had gesture-speech mismatches benefited from instruction more than other students (Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986; Perry et al., 1988). Researchers concluded that discordant children had an implicit understanding that was made explicit through instruction. Thus, gesture-speech mismatch is a characteristic that an individual has in a particular state which indicates receptivity to instruction (Alibali & Goldin-Meadow, 1993; Church & Goldin-Meadow, 1986; Goldin-Meadow, 2003; Perry et al., 1988). Accordingly, Goldin-Meadow and colleagues drew a learning trajectory as children transfer from the discordant to the concordant state (more will be discussed in the following section).

Additionally, the analysis of gestures and their relation to speech further reveal that some of the meanings revealed in gestures may appear first in the gesture modality then in the verbal modality (Givry & Roth, 2006; Goldin-meadow, 2003; Roth, 2000; Roth & Lawless, 2002c). To elaborate, when analyzing children's explanations of math equivalent problems, Perry et al. (1988) indicated that students produced six different strategies conveyed in gestures and/or speech: three types of equivalent strategies that conveyed correct explanations and three types of nonequivalent strategies that conveyed incorrect explanations. For example, when solving mathematical equivalence problem (e.g., 4+6+9= __ +9), a child said: *"I added 4 plus 6 plus 9 and that's equal 19; to make both sides equal, I had to subtract the 9 so the answer is 19"*. This articulation revealed using Adding-Subtracting equivalence strategy in solving the problem. The matching gesture for this type of verbal explanation was pointing at numbers 4, 6, then 9 on the left side of the equation; then, pointing at the equal side and sweeping across the blank space and 9 on the right side of the equation (Perry et al., 1988). Following that, the study conducted by Alibali and Goldin-Meadow (1993) further explored the type of strategies produced at each modality. Upon calculating the number of strategies produced by children in gesture modality, speech modality and in both speech and gesture modalities, researchers inferred that the equivalent strategies of discordant children appeared first in the child's repertoire in the gesture modality. They stated that "the first step a learner takes in acquiring a concept appears to be reflected in gestures" (Alibali & Goldin-Meadow, 1993, p. 511). Thus, researchers delineated a more specific learning trajectory. That is, they characterized the process of change to start from incorrect, concordant state expressed in both speech and gestural modalities. Then, learners acquire the correct representation in the gestural modality (and not in speech) where they enter the incorrect, discordant state. Finally, students enter a correct, concordant state after their knowledge had developed to acquire verbal expression of the correct representation.

Other researchers as well used the analysis of gestures and their relation to speech in order to draw a learning trajectory. Yet, while investigating this relation, they further identified the types of gestures produced by learners. The analysis of learners' gestures and speech by Roth and colleagues over an extended period of time (two to four months) revealed that the gestures produced by students lag behind speech. This lag may range from 400 ms to 1.40 s. Notably, it decreases as students become more knowledgeable about a topic and produce correct verbal explanations. Also, researchers suggested that as students become more familiar with a topic, they produce less deictic, iconic, and/or metaphoric gestures (Givry & Roth, 2006; Roth, 2000).

Roth and colleagues provided detailed examples to elaborate on that. In *Sign, deixis and the emergence of scientific explanations*, Roth and Lawless (2002b) noted that as students become more familiar with a topic, they produced less deictic gestures and articulated less indexical terms. That is, researchers noted that deictic gestures are accompanied by verbal indexical words such as "this" or "that". Accordingly, the analysis of data revealed that the use of deictic gestures and terms varied among students as they used 10 to 20 different terms in denoting the velocity and force arrows on the screen. For example, one of the students said "see that one is the force. This one is the direction". While saying "this", the student pointed to the upward vertical arrow on the screen. This arrow stands for the "velocity" of an object. The researchers proposed that the student used deictic gesture and indexical term as he had not yet learned about velocity. They further proposed that, after the student had learned about forces and velocity, he would have said "velocity is changed by a force". Thus, they concluded that when learning, the lag between deictic gestures and speech decreases (Roth, 2000; Roth & Lawless, 2002b). This may be accompanied by a shift from using deictic gestures to using words to refer or describe an object or illustration (Givry & Roth, 2006).

Givry and Roth (2006) and Roth (2000) further inferred that not only deictic gestures precede the emergence of abstract, science concepts but also, iconic and metaphoric gestures precede verbal speech. One of the provided examples was about a Grade 5 student (Jeff) who was explaining the strength of a bridge model that he constructed. In this example, Jeff was explaining to his peers the effect of the upright pillars' weights on the horizontal bridge truss and the forces distributed along the truss. The student articulated "so it [upright pillars] brings forces down on the ends, and then it is easier for a force to go across here.". While saying so, Jeff rested his hands on the pillars of the bridge. Then, while articulating "down the end", he moved his hands to the downward sides of the bridge pillars. Jeff then gestured with his right hand horizontally from the right side to the left side of the bridge. His horizontal movement was parallel to the truss of the bridge. This gesture was repeated twice when Jeff articulated "to go across here". The researchers inferred that this gesture depicted how forces are distributed on the horizontal truss. Notably, Roth and colleagues highlighted that the gesture was produced before Jeff articulated "forces". But also, they noted that the gesture delayed behind speech by 1000 ms after Jeff had investigated the bridge structure and became more familiar with the forces (Roth, 2000). Based on the former evidence, Roth and Lawless (2002b) concluded that a "learning trajectory is evident as learners begin their learning with a muddled talk (e.g., use of indexical term). Then, once students have developed consistent ways of verbally representing particular entities, the use of gestures decreases." (p. 122).

The preceding discussion (and based on the evidence provided by Goldin-Meadow, Roth and other colleagues) reveals when students are learning, there are changes in the gestures produced and their relation to speech. This includes a shift from the gestural modality to speech modality and a decrease in the lag between gestures and speech. Notably, more detailed analysis by various researchers reveal that learning might be accompanied by changes in the types of the gestures produced (see Givry and Roth, 2006) and the physical form of the gestures produced (Scherr, 2008).

To elaborate, Roth and colleagues suggested that as students are learning, they produce less gestures as they start relying on the verbal modality. The researchers further added that learning may be accompanied by changes in the types of gestures produced. The former inference was based on the analysis of the previous studies conducted by Roth (1999, 2001). Givry and Roth (2006) also proposed that as students are learning they may shift from using deictic to iconic gestures. This was evident as the student Gaalen in the previously mentioned example used deictic gesture to point for the "force" arrow on the screen. As this student learned more about force, velocity and the relation between them, he used iconic gesture that depicted the curvilinear movement of the object's trajectory present on the screen (Roth & Lawless, 2002b). Accordingly, Givry and Roth (2006) inferred there may be changes in the types of the gestures produced (e.g., from deictic to iconic) by some students as they are learning. But also, other students when learning, they may shift from the gestural modality to speech modality.

While Roth and colleagues identified changes in the types of the gestures produced, Scherr (2008) provided evidence for the presence of changes in the physical form of the gestures accompanying learning. In analyzing her previous work on gestures, Scherr indicated a relation between the physical form of gestures and changes in the state of students' ideas. That is, the physical form of gestures are indicators to the *novelty* of ideas whether to the communicator or to the listener as they reveal a shift in the state of ideas from newly constructed ideas to familiar ones. Scherr provided different examples to elaborate on this notion where she compared the gestures produced by students at two different instances. One of the examples was for a student who was explaining the backward movement of a vehicle upon colliding. Specifically, the gesture of the student changed from moving his body backward to gesturing with a loose backward hand movement. This was taken as evidence that the gestural form changed from being large, detailed and strong to being simple, small and less well detailed as students' state of ideas changed. This was also evident in the study conducted by Crowder (1996a) where he provided an example of a Grade 6 student who pointed to the globe while holding her thumb and finger separated in explaining the warm weather on the equator. This gesture is more specific and contains higher semantic content than a simple pointing gesture as it reveals the student is construing the equator as a region and not a line. Following that, Crowder inferred that as gestures become more specific, they acquire higher semantic content. He further proposed the presence of variation among students in the specificity of the produced gestures and explicitness of articulated speech. Based on that, we find the analysis of the physical form of gestures indicative of learners' state of understanding.

In sum of the above, different researchers have been interested in analyzing the gestures produced by learners whether in naturalistic contexts (e.g., Crowder, 1996a; Roth, 2000) or in one-on-one interviews (e.g., Alibali & Goldin-Meadow, 1993). When using gestures as an analytical lens, we find that gestures may convey information that is abstract, not accessible yet in speech, and/or different than that articulated in speech. Also, as learners are engaged in the process of learning and constructing new understandings, changes in the gestures produced and their relation to speech is evident. This includes changes in the three dimensions: physical form of the gestures produced, types of gestures produced, and changes in the relation between the gesture produced and its corresponding speech (e.g., gesture-speech mismatch). The evidence provided by different studies indicates that gestures may be considered as a productive method to understand learners thinking and learning.

Research Methodologies Adopted and their Limitations. In using gestures and speech as analytical lenses, learning and the changes occurring in learners' thinking are characterized differently based on the methodologies adopted by researchers. This was evident given the quantitative methodological approach adopted by Goldin-Meadow and colleagues and the qualitative methodological approach adopted by Roth and colleagues on the other hand. Not to mention that a methodological limitation is addressed by Roth and colleagues which was also evident in the argument existing between Cienki and McNeill regarding the classification of iconic and metaphorical gestures. The following paragraphs will elaborate on these notions.

The studies conducted by Goldin-Meadow and colleagues adopted a quantitative methodology in analyzing the relation between gestures and speech with emphasis on representational gestures (deictic, iconic, and metaphoric). These studies focused on investigating children's understanding and thinking at different ages while reliably attributing meanings to the gestures produced. In line with that, they recruited many participants in their studies (e.g., 28 children in the study conducted by Church and Goldin-Meadow, 1986). Additionally, they provided detailed numerical data for the frequencies and percentages of the produced gestures and for gesture-speech mismatches and matches. Statistical analyses were used for different purposes. One of which was for determining the relation between gesture-speech mismatches and children's receptivity to instruction (Church & Goldin-Meadow, 1986).

In contrast, the studies conducted by Roth and colleagues analyzed the types of the gestures produced and their relation to speech based on the analysis of video recordings of students gesturing in science classrooms or face-to-face interviews. They conducted mostly qualitative case studies. In these studies, researchers provided detailed analysis of the different gestures that students produce when learning science. This included detailed descriptions of the physical form of the gestures produced. That is, researchers selected cases and elaborated on them taking into consideration changes in the types of gestures produced and their relation to the co-occurring speech. A shortcoming of this line of research is that some of their conclusions were not based on quantitative data. It may be argued that they are overgeneralizations from selected cases. For instance, Givry and Roth (2006) inferred that a shift in conceptualization is evident as students: evolve in using modalities such as using words instead of deictic gestures or using iconic gestures instead of deictic gestures in expressing the same concept; coordinate the use of different words and types of gestures in communicating the same concept; and change in the link between speech and gesture such as decrease in speech-gesture mismatch, decrease in speech delay, and/or decrease in the frequency of used gestures. Though researchers produced the former inferences, they were not supported by quantitative data. In line of the above, it would be interesting to conduct a study that balances between quantitative and qualitative methods by increasing the sample size while providing detailed examination of learners' problem solving.

Furthermore, a challenge is raised by researchers when classifying and differentiating between iconic and metaphorical gesture. This was hinted from the argument between Cienki (2008, 2016) and McNeill (1985, 1992) and further discussed by Roth and other colleagues. In *Scientific investigations, metaphorical gestures, and the emergence of abstract scientific concepts,* Roth and Lawless (2002a) presented an example of a grade five student (Jeff) gesturing when explaining forces enacted on the bridge model. This example was elaborated in the previous sections. Roth and Lawless (2002a) and Roth (2000) considered the gesture produced by Jeff is metaphorical enacting conduit metaphor as had been indicated by McNeill (1992) since "there is no precedence, no experience that would have allowed him to actually see or otherwise perceive the forces. Here, the forces in structures are abstract concepts not directly available to experience" (p. 292). Roth (2000) added that this gesture represents forces that are acting on the bridge which are vectors "they cannot be pointed to, but have to be indicated in terms of magnitude and direction. Here, in this first part of the episode, Jeff gestured the direction in which the weight of the pillars acted." (p. 1705). Yet, one can note that this gesture has an iconic component as it depicts a *direction*. This poses a question: Is the gesture produced by Jeff may be classified as iconic or metaphoric knowing that the analysis of speech reveals discussing an abstract notion (i.e. force)? However, this gesture is considered metaphorical according to the definition of metaphoric gestures provided by Roth and Lawless (2002a). In this article, researchers extended the definition of metaphoric gesture to include gestures that "are used to denote abstract scientific entities (concepts) and processes that are used for explanatory purposes but are not available to perception." (p. 290). Roth (2000) further distinguished between iconic and metaphoric gestures based on their referents: iconic gestures refer to material objects and events while metaphoric gestures to abstract concepts.

Finally, Roth and Lawless (2002b, c) concluded by raising the issue of classifying gestures as iconic while questioning the degree to which iconic gestures actually represent iconic information. The researchers indicated that more research is needed from future researchers who are interested in investigating the nature of iconic gestures. Especially that it is not clear how we can classify iconicity in the gestures produced in the context of explaining science. Thus, classifying the produced gestures as either iconic or metaphorical is a challenge for science educators specifically since the nature of science concepts is abstract. This was highlighted as well by Richard Feynman as mentioned in previous sections.

Do Gestures Provide Evidence of Ontological Categorization? Researchers in the field of conceptual change have typically used speech as a unit of analysis when investigating novices and experts' ontological categorization. Little research has been done that uses gestures as a unit of analysis to investigate the ontological categorization of science concepts. Two studies conducted by Dreyfus and other colleagues, however, have used gestures, drawings and speech in analyzing novices and experts' ontological categorization. In these studies, the researchers aimed at providing evidence for flexibility in students' thinking about physical concepts.

The methodology developed by Dreyfus et al. (2015a) was based on the studies conducted by Goldin-Meadow and colleagues in which, they analyzed first the content of the speech then they analyzed the gestures produced. Following that, the researchers mentioned that they developed multiple interpretations for the meanings that may be conveyed by participants' gestures. Then, based on the co-occurring speech, researchers selected a particular interpretation. In doing so, Dreyfus et al. (2015a) analyzed the gestures produced and their co-occurring speech to determine gesture-speech mismatches. In this study, mismatches were taken as evidence that students and/or the professor are invoking two different ontological categorizations at the same time providing evidence in support of the dynamic view of ontology. Similar to Goldin-Meadow (2003), researchers were interested in analyzing (1) metaphorical and iconic gestures and (2) deictic gestures. Yet, unlike the studies conducted by Goldin-Meadow and colleagues, in analyzing these types of gestures, Dreyfus et al. (2015a) adopted an interpretive approach since "it is difficult for us to make an exhaustive list of what particular gestures are coded for which ontology or metaphor" (p. 825). In this study, researchers analyzed data of a professor explaining in a classroom context about the changes in energy levels when two atoms are breaking bonds. In addition to that, they analyzed data from a follow-up interview conducted with one of the professor's students (Betsy) where she was asked to explain which of the drawn two graphs represented more energy.

In this study, researchers provided two examples which reveal the professor and the student straddled ontologies. To elaborate, one of the examples was for the student Betsy saying, "it doesn't actually hold energy, like it's not—like, the bond itself doesn't have a lot of energy, but it's the fact of breaking it and forming this is even more—is even lower energy*"*. The analysis of verbal modality -and based on the coding scheme developed by Slotta et al. (1995)- revealed that the predicates "hold energy", "have a lot of energy", and "energy given off" indicate using Energy as a Substance ontology. However, the predicates "lower energy" and "here" reveal invoking Energy as a Vertical Location. Also, analysis of gestures indicates using Energy as a Vertical Location where the student pointed to the vertical axis of the graph. Based on that, researchers inferred the graph drawings and the gestures produced (including indexical terms e.g., here) reveal invoking Energy as a Vertical Location while the speech analysis reveal invoking Energy as a Substance ontological metaphor.

In response to the data analysis procedure adopted by Dreyfus et al. (2015a), Núñez (2015) critiqued Dreyfus et al. on their interpretative gesture analysis methodology. Núñez noted that the gestures that had been documented as invoking Energy as a Vertical Location metaphor are pointing gestures that co-occur with deictic terms such as *here*, *this*, or *that*. Instead, Núñez proposed that these gestures serve the function of being complementary to speech. Thus, these gestures don't provide evidence of Energy as a Vertical Location metaphor. Following that, Núñez proposed that using deictic gestures and terms (e.g., here) and demonstratives (e.g., this and that) as evidence for blending two ontological metaphors is insufficient. In line with that, the commentary provided by Núñez recommended the need for future studies that (1) use more rigorous empirical methodologies to provide readers with enough evidence to develop alternative conclusions especially as they study of Dreyfus et al. (2015a) only provided two examples and didn't provide readers with enough evidence to interpret data differently; and (2) be more specific in what counts as evidence in research.

Concluding Thoughts

It is evident that a disagreement exists between proponents of the dynamic view of ontology and the OS theory on their view of the nature of leaners' conceptions, the difficulty learners face in learning some science concepts and the instructional approach adopted. Two methodological issues were raised in this review: language has been the main analytical lens used to investigate novices and experts' ontological categorization and the methodological approach adopted by proponents of both views is limited to either quantitative or qualitative methods.

The existing argument between Hammer, Gupta and Slotta reveal proponents of both views either used quantitative or qualitative methodologies in building their arguments. On the one hand, the studies conducted by proponents of the dynamic view of ontology have been limited to qualitative case studies with small sample sizes (e.g., Gupta et al. (2010) and Dreyfus et al. (2015a)). This aided in providing in-depth analysis of cases. Yet, the collected data can't be generalized to infer that learners and experts generally straddle ontological categories. In contrast, the studies conducted by Chi and colleagues were in vitro where development of expertise is evident in the *frequent* use of process predicates among *numerous* participants. Accordingly, researchers generalized that novices categorize science concepts within the matter category while experts think of science concepts as a process.

In addition, proponents of both theories used language as an analytical lens onto learners and experts' ontological categorization. The use of gesture as an analytical lens to uncover learner and expert categorization of science concepts has been limited. The study conducted by Dreyfus et al. (2015a) did use the analysis of gestures, language and visual representations to investigate learners and expert ontological categorization but was critiqued by Núñez (2015) on methodological grounds. Additionally, it can be noted the analysis provided by Dreyfus et al. (2015a) is based on a qualitative case study that provided detailed descriptions of two examples only.

Accordingly, the study being proposed here is a replication of the study conducted by Slotta et al. (1995) but adds the analysis of gestures as an analytical lens alongside speech. Additionally, to address the existing argument between proponents of both views, the current study will adopt a mixed-methods research design that balances between quantitative and qualitative approaches. This will be done by increasing the sample size while providing detailed analysis of learners and experts' problem solving. The evidence provided here will represent a contribution to the field as it will address the disagreement existing between proponents of both views. Specifically, it will provide evidence whether learners and experts categorize science concepts into two distinct categories or not. This will affect which instructional strategy is considered effective in overcoming the difficulty students' face in learning and thinking about science. Thus, this study addressed the following research questions:

1. What types of gestures do novices and experts produce while solving physics problems and how do they differ?
2. Do some of the gestures novices and experts produce while formulating science explanations provide evidence of ontological categorization of science concepts?

3. Do speech and gesture analyses reveal the same ontological categorization of concepts in science explanations?

CHAPTER III

Methodology

Overview of Research Design

The focus of this study was on comparing novices and experts' ontological categorization of science concepts. To do so, the analysis of both speech and gestures was used to determine the ontological categorization of science concepts at different levels of expertise. Therefore, the current study followed a comparative descriptive research design that compared the ontological categorization of experts and novices. Additionally, it compared whether the ontological categorization revealed by speech was similar to that revealed by gestures.

As such, participants were provided with a set of problems similar to those provided by Slotta et al. (1995). However, fewer problems were presented (18 compared to the 36 used by Slotta et al.) given the time-consuming nature of the analysis of both language and gestures for each explanation for each participant. The problem-solving sessions were video recorded and both speech and gestures were analyzed to determine whether they reveal Matter or Process predications. That is, the coding taxonomy developed by Slotta et al. (1995) was used in the analysis of both gestural and verbal predications. Specifically, the analysis of speech followed the coding scheme developed by Slotta et al. (1995) while the gestures produced were analyzed using procedures based on prior work conducted by gesture researchers (Cienki, 2010, 2016; Goldin-Meadow, 2003; McNeill,1992) and in addition to the work of Lakoff and Johnson (1980) and Johnson (1987) on the theory of conceptual metaphor.

The procedure of analysis of verbal and gestural data consisted of four phases. Initially, participants' speech was first transcribed and analyzed separately with the visuals turned off.

This aided in the identification of verbal predicates. Then, gestures were analyzed to isolate, identify and classify them based on their referents. It shall be noted that the current study targets three science concepts: heat, light, and electric current. Only gestures that reveal metaphors related to the three targeted concepts were used in the identification of predicates. Following that, the identified gestural predications were compared with verbal predications to identify gesture-speech pairs. Following that, the extent to which novices and experts consistently categorize science concepts into the matter or process ontological categories was determined.

In this study, qualitative and quantitative analyses were conducted. The data analysis techniques included reporting descriptive statistics including frequencies and percentages of matter and process predicates. Furthermore, statistical analysis - including Chi-Square and two by two Analysis of Variance (ANOVA)- were used to test whether there was a difference in the gestural movements and types of gestures produced by novices and experts (i.e., Question 1) and in analyzing the predicates used by participants in each modality and in each problem (Question 3). Qualitative analyses included probing and comparing patterns of in/consistencies in participants' explanations to address the third research question.

Participants

Given the purposes of this study, data was collected from eight participants that were of different levels of expertise: four novices and four experts.[6] Recruiting this number of participants aided in providing a detailed analysis of learners and experts' problem-solving. The

[6] Data collected from one additional expert was not included since the participant was holding a cup in her hand which constrained her movements: using data collected from this video recording would have influenced the analysis. Thus, only four video recordings of experts were used in the analysis of this study.

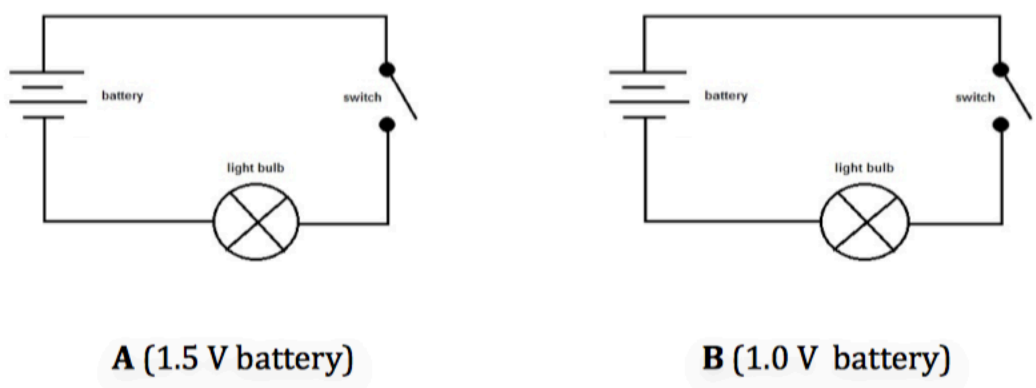
recruited participants were from a private university in Beirut that uses English as its language of instruction, and they were of different educational backgrounds. That is, novice learners were undergraduate students (above 18 years of age) who had limited knowledge in science as they were not majoring or planning to major in a science discipline. Specifically, they were majoring in Computer Science, English Literature, Graphic Design, and Communication and Political Science. During the interview, learners were asked whether they had taken a natural science course. Participants stated that they had taken general science courses except for one novice who had taken an introductory course in physics. Among these learners, three were seniors and one was a junior. As for experts, they were university professors in the fields of Geology, Chemistry, Physics and Chemical Engineering. All of the university professors indicated that the language in which they teach and publish about their areas of expertise is English. The full profile of participants is present in Appendix C.

Data Collection Tools

Similar to Slotta et al. (1995), participants were provided with eighteen problems divided into two sets: nine physics-concept problems and nine material substance isomorph problems. These problems were multiple-choice questions composed of four options where participants had to predict the outcome of a situation. The physics-concept problems targeted the concepts electric current, heat, and light. In these problems, one option was scientifically correct, and one option, if selected, revealed that participants had material misconceptions. Also, the third option was a general response that provided a distractor from the first two responses and the fourth option was “other” to control for guessing. Each physics-concept problem was paired with material substance isomorph. Figure 3 provides an example of an electric current problem. This problem is paired with a material isomorph problem that had the same structure yet involves prediction about two identical cars having different gas tanks. The misconception targeted in this problem was the material construal of electricity *running out* analogous to the idea of a car running out of gas. (Appendix B provides the set of problems that were provided to participants and developed by the thesis advisor).

Physics Concept Problem

9A. The two circuits below are identical except for the battery. In circuit A, it is a 1.5 Volt battery. In circuit B, it is a 1.0 Volt battery.



Which of the following predictions is correct?

a. The battery in B will turn off before the battery in A.
b. Both batteries will turn off at the same time.
c. There isn't enough information to determine which battery will turn off first.
d. Other

Material Substance Isomorph

9B. Two identical cars have been fitted with different sized gas tanks. The tank in car A is 1.5 times the size of the tank in car B. Which of the following predictions is correct if both cars are traveling at the same speed having begun with a full tank of gas?

a. The tank in car B is filled of gas before car A.

b. The tanks in both cars are filled with gas at the same time.

c. There isn't enough information to determine which car of gas first.

d. Other

Figure 3: Example of an electricity problem with its material isomorph as in Slotta et al. (1995).

Data Collection Procedures

Data was collected in one-on-one sessions between the researcher and each participant. Each problem-solving session lasted about 40 minutes. Data was drawn from two sources: videos of participants' explanations and multiple-choice responses. The camera was placed at a location that provided clear and focused visual recordings of participants' gestures so that they can be identified, described and subsequently categorized. Additionally, this set aided in capturing their verbal explanations clearly.

When collecting data, participants were first presented with the physics-concept problems as a block followed by material problems to avoid the influence of the material substance isomorph problems. They were told the session includes a series of multiple-choice problems. They were asked to read each problem, which asks for a prediction of an outcome of some event, select the preferred prediction and explain their prediction. As participants were providing their explanations, the researcher requested further clarifications such as "can you give a deeper explanation? Or can you elaborate on that? Or what did you mean by saying that?" Probing questions by the researcher were kept to a minimum for reliability purposes. Also, the researcher didn't gesture as this might have influenced participants' gestures. This was evident in the study conducted by Church and Goldin-Meadow (1986) were one of the types of gestures identified (i.e. iconic gestures) resulted from children mimicking the movements produced by the experimenters. Abels (2016) also noticed some students in his/her study produced the same gestures that had been produced by the teacher. Notably, Perry et al. (1988) and Alibali and Goldin-Meadow (1993) avoided this issue by limiting the gestures of the trainer/researcher to those that would not reveal any meanings of relevance to their studies. Thus, given the purpose of the current study, it was suggested that the researcher not gesture at all as this might influence the gesturing of participants. Also, participants were not provided with a pen or pencil when solving these problems. This is the case since the act of drawing is not considered gesturing and providing participants with a pen/pencil would have influenced (or constrained) the gestures produced. Instead, participants were presented with the problems projected on a screen. After the researcher read the problem aloud, participants were requested to provide the correct answer. Following that, they were asked to provide explanations for their choice. The same procedure was applied to all of the problems.

Data Analysis Procedures

Data analysis in this study included frequency tabulations and statistical analyses (Chi-square and two-by-two ANOVAs). First, participants' responses on multiple-choice questions were analyzed to determine the frequency of correct answers. Then, participants' explanations were analyzed in four phases. That is, the analysis of verbal explanation followed the same procedure developed by Slotta et al. (1995). However, the approach for analyzing gestures and determining gestural predications was developed based on prior research by McNeill (1992), Goldin-Meadow (2003) and Cienki (2010, 2016). It was further supported by the work of Lakoff and Johnson (1980) and Johnson (1987) on the theory of conceptual metaphor and their analyses of typical image schemas making up the source domain of some metaphors.

The first phase involved transcribing participants' speech alone without the visuals followed by determining the verbal predications and the OC they correspond to. Speech was analyzed in a way similar to Slotta et al. and using their predicate analysis procedure to determine novices and experts' ontological categorization explained below. The second phase involved the transcription of participants' gestures with the audio turned off initially to identify, isolate and subsequently classify gestures based on their contextual referents. The third phase involved selecting metaphoric gestures that are predicating the three targeted concepts (heat, light and electric current) and further identifying the ontological category they correspond to. Finally, the last phase of the analysis represented the analyses of speech and gestures together to analyze concurrent gesture-speech pairs. To ensure reliability of the abovementioned coding, inter-rater reliability was established by having a second trained coder independently code the speech and gestures produced by participants, to classify the gestures produces, identify their referents, and identify the gestural and verbal predications and the category they correspond to.

Verbal Predicate Analysis Procedure. In analyzing the predicates used by novices and experts, verbal explanations were coded using the taxonomy developed by Slotta et al. (1995) with the visuals turned off. Slotta et al. developed a coding scheme for analyzing novices and experts' explanations that was composed of matter and process predicates. Appendix A provides a sample of the predicate coding scheme developed by Slotta et al. These predicates are reflected in words or phrases articulated by participants when explaining the problems.

First, the video recordings were transcribed to a written form. Second, data was coded according to Slotta's et al. taxonomy as present in Appendix A in order to calculate the frequency of each predicate used. The total frequency and percentage of predicates used were calculated. To find the percentages, data was normalized as some explanations were lengthier than others. For each participant, the occurrence of a particular predicate was divided by the total number of predications. For example, in order to find the percentage of matter predicates produced by experts in the verbal modality in the heat problems, we divided the total matter predicates produced by experts in the verbal modality in the heat problems (i.e., 15) by the total predicates produced by experts in the heat problems (i.e., 30). This value was then multiplied by 100. It shall be noted that the study conducted by Slotta et al. (1995) divided the total frequencies by “idea units which could range from a single phrase to several sentences in length, as determined by informational content (p. 396)”. We opted to not use this method as it would raise the challenge of identifying idea units clearly and objectively. To elaborate, Cienki (2005) indicated that an *idea* may be expressed verbally through speech content and through gestures (Cienki, 2005). This was also supported by McNeill and Duncan (2000) as they stated that “By looking at the speech and the gesture jointly, we are able to infer characteristics of this underlying idea unit that may not be obvious from the speech alone.”. Consequently, identifying *ideas* articulated in speech and that revealed in gestures requires a discourse analytical framework which is beyond the purposes of this study.

By the end of this phase, the collected data were entered on the Statistical Package for Social Sciences (SPSS) software for analysis. Chi-Square Test and two-by-two Analyses of Variance (ANOVA) was conducted. Specifically, Chi-Square Test was conducted to determine whether any differences in the pattern of frequencies of different gestural types produced by participants, both novices and experts, across the three targeted science concept problems were significant. Furthermore, ANOVA (2X2) was conducted to determine whether there is a significant difference between the speech predicates produced in participants’ explanations and the types of problems across different levels of expertise. It was hypothesized that the results of the predicate analysis in this study would be similar to the results revealed by Slotta et al. (1995) where novices used material substance predicates more frequently when explaining both types of problems while experts used process predicates more frequently when solving physics-concept problems.

Gesture Analyses Procedure. There has been no prior research that has systematically examined the analysis of gestures as a window onto ontological categorization. Thus, the analytical framework of the current study is based on synthesis of prior work by various researchers: Goldin-Meadow (2003), Cienki (2010, 2016), and McNeill (1992), and guided by the study's research questions as has been recommended by Cienki (2008). The developed procedure of analysis is composed of four phases:

Phase one.: Gestural Identification. The initial phase for analyzing gestural movements was performed with the audio turned off based on the work of Goldin-Meadow (2003) and McNeill (1992). In this phase, gestures were first isolated from other body movements and following that the gestural movements were described. Novack and Goldin-Meadow (2017) and McNeill (1992) set criteria for isolating gestures from other body movements. They indicated that the manipulation of objects is not considered gesturing. Specifically, gestures were defined as movements that have a communicative function, represent information of some kind and co-occur with speech. Thus, a movement was considered a gesture if it met three criteria: (1) it occurred off objects (e.g., drawings are not counted as gestures); (2) it was produced to communicate (e.g., stroking the hair is not considered as gesturing); and (3) it co-occurred with speech. Then, the gestural movements were described as had been proposed by Cienki (2016), McNeill (1992), and Perry et al. (1998) based on three dimensions: hand (which hand or both hands, shape of the hand and palm and finger orientation); movement (shape and direction), and placement of hands (place where the hand or finger is directed). The reason for providing a description for the hand movement and shape is that some of the gestures may be stationary such as holding two hands in a circular shape in front of each other as if holding an object when explaining the instability of positive charges (Chue et al., 2015). They may also involve movements of the hand(s) such as moving the hand up and down when explaining the movement of molecules in a syringe (Givry & Roth, 2006).

It shall be noted that in the analysis of gestures, the focus was on the stroke phase with the assumption that the researcher is able to identify strokes as distinct from preparation and post-stroke, and retraction. This is based on McNeill's (1992) identification of phases in any gestural movement:

- Preparation phase: It refers to the moving away from the hands' rest position to a position in the gesture space where the stroke begins.
- Stroke phase: It is the most active phase where the meaning of the gesture is expressed. The post-stroke phase occurs by the end of the stroke phase where the hand movement is at hold mostly due to speech delay.
- Retraction phase: It is the phase where the hand returns to its rest position. The preparation and retraction can be optional; the stroke phase is obligatory.

In this study, there was no explicit identification of strokes given the number of gestures produced and the number of participants recruited. But there were cases where the identification of the different phases needed to be resolved with discussion with a second researcher. This phase of analysis aided in identifying gestural movements produced by participants which helped in classifying gestures.

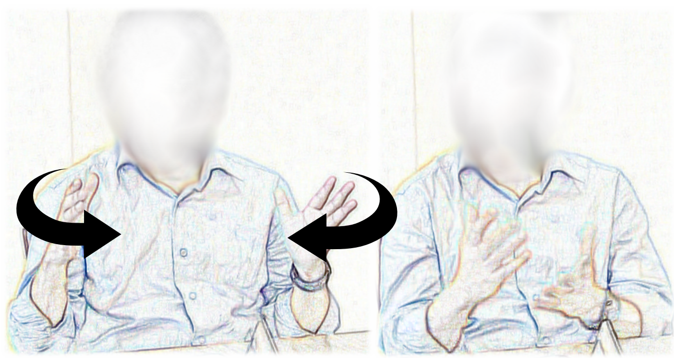
Phase two: Gestural classification. The second phase of the analysis aimed to classify gestures based on their referential functions as proposed by Cienki (2010, 2016) which targets the first research question (i.e., what are the types of gestures novices and experts produce and how do they differ). The term "reference" is defined by Cienki (2016) as "interpretation of what the speaker may have had in mind when producing the gesture in light of the speech with and around it." (p. 202). Cienki (2010, 2016) proposed the classification of gestures based on their contextual referent: abstract or concrete. That is, given the context of speech and its temporal proximity, some gestures may be referring to an abstract or concrete topic. The following is the classification proposed by Cienki (2016). Appendix E provides examples from this study on how gestures were classified.

- Concrete Referential Gestures: These gestures are referring to a concrete topic. They are of two types: iconic and deictic.
    - Iconic gestures: These are gestures where the "referent may be a physical entity, relation, or action, in which case the gesture normally involves some kind of iconic representation of some feature(s) of the referent." (Cienki, 2010, p.139). These gestures are referred to as iconic gestures based in McNeill (1992) gesture classification.
    - Deictic gestures: They are pointing movements that are referring to concrete object which may not be seen in the moment.
- Abstract Referential Gestures: These are gestures where the speech context is abstract, and the gestures are representing a metaphor. These can be classified into metaphoric and deictic.
    - Metaphoric gestures: They are gestures that are referring to an abstract concept via their motion and their physical form.
    - Deictic gestures: They are pointing gestures that are referring to a "physical referent when the space is not construed by the speaker as metonymically grounded by the referent, e.g. pointing to a space on the left to refer to one character and a space on the right to refer to another character in a story that one is telling." (Cienki, 2016, p. 140)

- Non-referential gestures: This class of gestures include beat gestures and discourse markers (Cienki, 2016). McNeill (1992) defined beats as simple hand movements that don't convey information and are used to emphasize a word or phrase (McNeill, 1992). For example, beats can be movements of the hand in up-and-down motion, back and forth movements, or waving (Crowder, 1996a, b). As for discourse markers, they are gestures that divide a space to locate abstract ideas. These are also considered as metaphoric as they concretize abstract ideas.

To classify gestures as proposed by Cienki, following the description gestural movements, we (1) identified the physical referent referred to with the gesture; (2) identified the contextual topic articulated in the speech; and (3) determined whether the gesture is representing a metaphor or not. The physical referent represents the object/entity embodied in hand/movement while the contextual topic represents idea that is being communicated as indicated in the speech and gesture combination. However, to be able to determine whether the gesture depicts a metaphor, the analysis of gestures was supported by the work of Lakoff and Johnson (1980) and Johnson (1987) on the Conceptual Metaphor Theory and the image schemas underlying conceptual metaphors that they have described.

Following the CM theory, humans conceptualize abstract concepts based on concrete experiences (e.g., moving, holding, pushing objects …etc.). Abstracting across many similar experiences forms image schemas which can be mapped into abstract concepts to form a metaphor. That is, image schemas are defined as "structures based on bodily experiences that organize our conceptual system at a more general, abstract level" (Brown, 2003, p. 38). For example, consider the container schema: it is based on our everyday interactions with objects moving in/out of containers such as cups, rooms, houses …etc. (Johnson, 1987). This schema has an in-out orientation and it can be embodied in the gestures produced as well. Figure 4 illustrates how a metaphorical gesture was analyzed. In this example, the hand movement had an in-out orientation indicating a container image schema. In this case, the physical referent of the gesture is an object moving in and out a container, and the contextual topic is the abstract concept of heat going outside the Styrofoam cup. Consequently, this gestural movement reveals metaphorically construing heat as an object that is contained and moving outside the boundaries of a container. Appendix F provides a list of image schemas discussed by Johnson (1987) which supported the analysis of metaphorical gestures and aided in the identification of matter and process predicates.



Speech	*It [Styrofoam cup] is an insulator (a), it will not allow heat to pass easily (b) like the ceramic mug.*
Gesture	The physical referent is an object that is bounded. Contextual topic is heat being insulated/trapped in the mug. Thus, heat is metaphorically construed as something that is contained.

Figure 4: Example of how a metaphorical gesture was analyzed

Finally, to address the first research question (i.e., to compare the gestures produced at different levels of expertise), the overall frequencies and percentages of the types of the gestures produced by novices and experts were determined. To normalize the frequency of gestural types, the frequency of a particular gestural type was divided by the total number of instances of a gestural type that was produces in an explanation rather than by the total number of instances of gestural *movements*. This was because “most gestures are multifaceted—iconicity is combined with deixis, deixis is combined with metaphoricity, and so forth.” (McNeill, 2005, p.38). Thus, some gestural movements may have more than one function – e.g. both deictic and iconic. To elaborate, the analysis revealed a total of 28 gestural movements that combined more than one gestural type. In some cases, beats were superimposed on metaphoric, iconic and deictic gestures. Also, some gestural movements functioned as both deictic and metaphoric. This helped in accounting simultaneously for the deictic function of the gestural movement and the metaphor embodied in it. Table 1 presents an example from Expert 2 for the overall frequency of gestural types produced in individual concept problems. For example, to find the percentage of metaphoric gestures used in heat problems we divided 4 by 13 which is the total gestural types and multiplied by 100. Thus, the percentage frequency of metaphoric gestures produced in heat concept problems is 30.76%.

Table 1.
Table presenting the frequency of gestural types produced in individual physics concept problems by Expert 2.

Gestural Type	*Heat*	*Light*	*Electricity*
beat	8	22	5
iconic	0	8	4

metaphoric	4	18	6
other	0	0	0
deictic	1	9	4
Total Gestural Types	13	57	19
Total Gestural Movements	12	55	19

Phase three: Identification of gestural predications. This phase of gestural analysis aimed to determine whether gestures provide evidence of ontological categorization or not (i.e., 2nd research question). However, it shall be noted that not all gestures reveal a predication. As previously mentioned, a predicate is a description (communicated via a phrase or gesture) that reveals how a particular concept is construed, i.e., thought about. In this thesis, gestures were also used an analytical lens onto ontological categorization. Thus, a gestural predicate is defined as a referential gesture that reveals a metaphorical construal of a particular concept, specifically heat, light and electric current. For example, an iconic, referential gesture that represents the height of the cup doesn't reveal any predication: it is only representing iconically the dimensions of the cup. Rather, the previous example of metaphoric gesture presented in Figure 4 was predicating the concept heat. This gestural predication corresponds to the matter category where heat is construed as a substance that is contained. In contrast, Figure 5 illustrates how a produced gesture is predicating the concept temperature and not heat. In this example, the identified physical referent is embodying a movement along a linear scale while the contextual topic is explaining the temperature difference between the material. On that basis, this movement reflects metaphorically construing temperature as a quantity that is located on a scale and change of a quantity is a change in location in space. Thus, the predicated concept is temperature rather than heat. Identifying what is being predicated in gestures represented a challenge, and instances where the targeted concept was unclear to identify was resolved by discussion with another researcher. Appendix G provides further examples on how gestures were analyzed for identifying metaphors and their predications.

Speech	*Basically, this is a metal, metal conducts heat and the form of heat is through the equation Newton's equation in terms of the conduction of heat so it depends on the thermal conductivity of the material and the temperature difference.*
Gestures	The right hand has a fist shape except for the thumb and the index which are open with a distance between them. The hand is located at the center of the body. Then the hand rotates from the center towards the extreme right side (x2).

Figure 5: Illustration for E1 showing metaphoric gesture predicating the concept of temperature (not heat) produced when explaining a heat problem.

Phase four: Analyzing Concurrent Gesture-Speech Pairs. The last phase of the analysis represented analyzing gestural and speech predications to address the 3rd research question. Appendix H provides examples of consistent and inconsistent pairs and illustrates how concurrent gesture-speech pairs were analyzed and the challenges faced. Probing patterns aimed at identifying in/consistencies for each participant was based on the analysis of concurrent gesture-speech pairs produced in individual science concepts (heat, light and electricity). This phase of analysis was supported by calculating the frequency of concurrent gesture-speech pairs and the frequency of consistent and inconsistent pairs. Subsequently, this phase of analysis aided in exploring the extent to which there is consistency in the use of predicates within an individual participant or the production of predicates varied depending on context.

Reliability

The question of reliability in coding gestural types, speech predicates, and gestural predicates was addressed by having an independent rater code the explanations of two participants (one expert and one novice); this constituted approximately 25% of the data. The rater required approximately two hours of training then was provided with 6 problems to code: three science concept problems (one heat, one light and one electric current) and three corresponding material isomorph problems. The independent rater was requested to follow the same procedure of speech and gesture analyses adopted in this study. That is, she was provided with the transcript and was requested to describe the gestural movements produced, classify gestures based on their functions, and identify gesture and speech predicates. After that, a two-hour meeting was conducted with the rater to discuss how she had coded verbal and gestural data and further compare her codes with the codes of the researcher. On that basis, percentages of agreement were established for (1) gestural types; (2) gestural predicates; and (3) speech predicates. Instances of disagreements were resolved through discussion (see Figure 6 below). Following that, percentages of agreement was established for (1) agreeing to code an instance and (2) agreeing what the code shall be coded. Then after discussion, a percentage of agreement was also calculated. Results are reported in Table 2. Such approach yielded in high level of agreement after discussion: The agreement for gestural types were 96%, 90% for gestural predicates, 84% for science concept problems, and 90% for material isomorph problems.

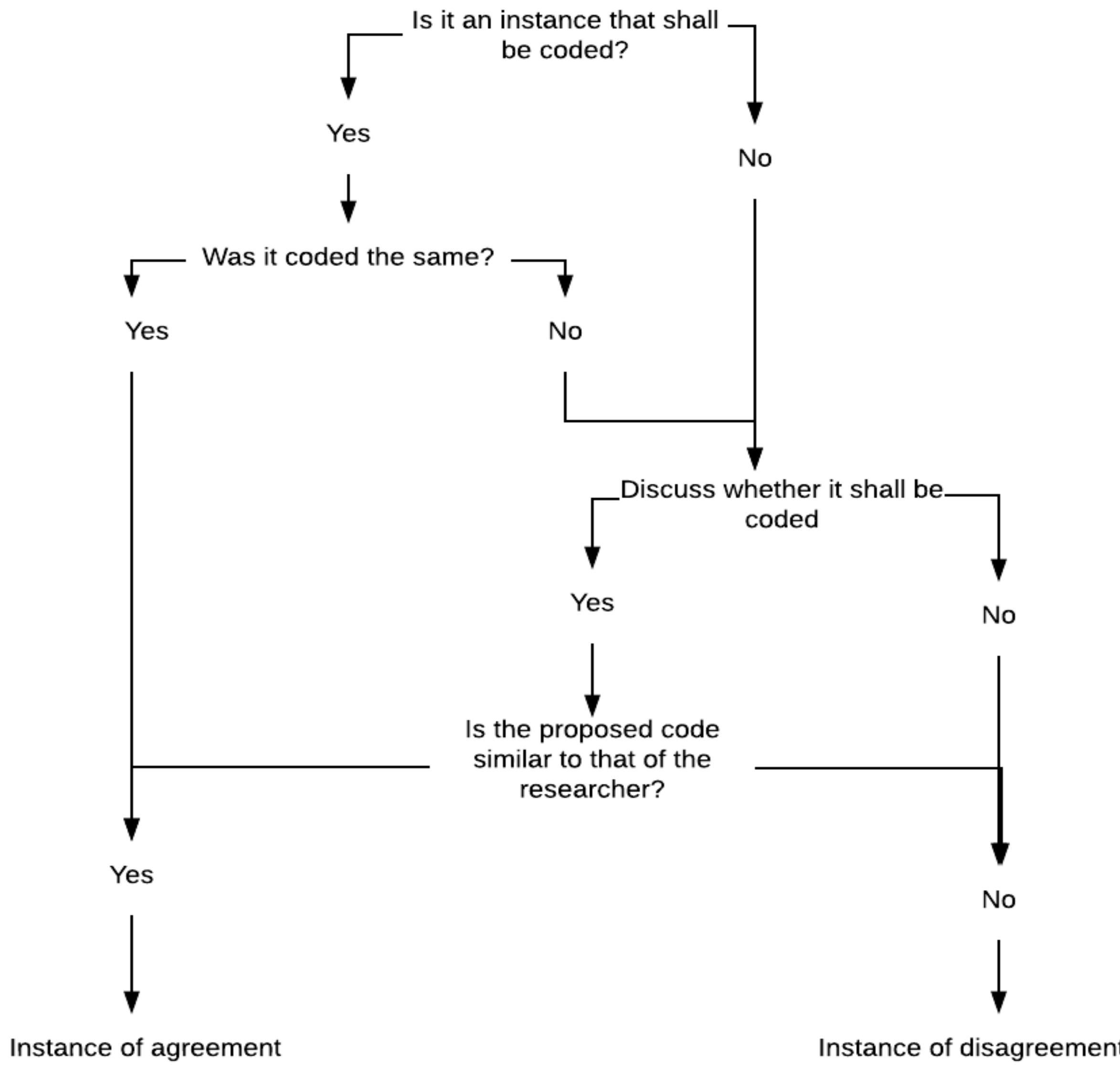


Figure 6: Illustration elaborating how agreement had been established

Table 2.
Table presenting percentages of agreement for gestural types, speech predicates, and gestural predicates

Problem Type	*Agreement Percentages*	*Agree to code an instance*	*Agree on the code*	*Agreement After discussion*
Science Concept Problems	Gesture Types	99%	96%	96%
	Speech Predicates	95%	85%	90%
	Gesture Predicates	85%	74%	84%
Material Isomorph Problems	Speech Predicates	83%	90%	90%

CHAPTER IV

Results

The results of this study are presented in three sections each targeting the posed research questions. The first section aims to address the first research question where results of the types of gestures produced by participants when formulating science explanations are presented. Then, the second section addresses the second research question where the classified gestures were analyzed to identify the gestural predicates produced. Finally, the third section presents the results addressing the third research question where verbal data was analyzed based on the analysis procedure developed by Slotta et al. (1995) in addition to the analysis of participants' concurrent gesture-speech pairs.

First Research Question: Analyses of the Types of Gestures Produced

The first research question explored the types of the gestures produced by novices and experts when formulating science explanations. Specifically, the procedure for identifying and classifying the gestural types was based on synthesis of previous research conducted on gestures and their classification as discussed in the methodology chapter. To address this research question, the types of the gestures produced by novices and experts were compared in all the physics concept problems and distributed over the problem sets dealing with the different target physics concepts. Appendix E provides examples of how gestures were classified, and the challenges faced.

Comparison of Gestural Types. All of the gestural movements produced by participants when formulating science explanations were classified based on Cienki (2010, 2016) (see Chapter III for details). Analysis of gestural movements revealed that experts produced a total of

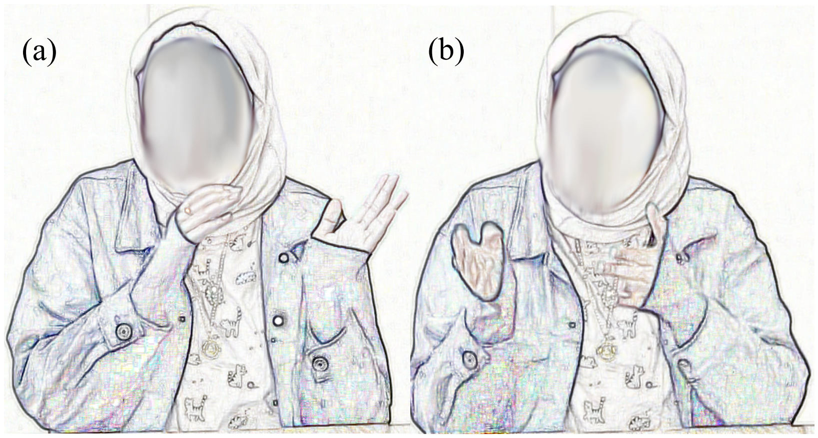
393 gestural movements while novices produced 312 gestural movements (see Table 3). The results of the analysis of participants' gestural movements revealed variation in the gestural movements produced by experts and novices across the science concept problems. These differences were significant (χ^2= 6.270 df=2, p<0.05). The novices produced more gestural movements in heat concept problems (44.55 %) than in light concept problems (25.32%) and electric current concept problem (30.13%). Yet, there was little variation in the gestural movements produced by experts across the science concept problems.

Table 3.
Percentages and Frequencies of Gestural Movements Produced by Experts and Novices in Individual Science Concept Problems

Participants	Heat		Light		Electricity		Total	
	f	%	f	%	f	%	f	%
Experts	148	37.66	145	33.84	150	28.50	393	100.00
Novices	139	44.55	79	25.32	94	30.13	312	100.00
Total	287	38.01	224	29.67	244	32.32	705	100.00

These identified gestural movements were then classified based on their functions into four gestural types: iconic, metaphoric, deictic, and beats. Notably, some gestural movements were too ambiguous to classify. These gestures were referred to as Other. For all the gestures that were treated as Other, it was unclear (and given the context of speech) whether they were referring to concrete or an abstract entity. For example, participant N3 produced a straight horizontal movement from left to right when articulating "if the switch is on... if it's off it will not work (if it's on it will work)." One possible analysis for this gestural movement is that it reveals metaphorically construing electric current as a substance that is moving. Another possible interpretation is that this gestural movement is iconically representing the shape of the electric circuit diagram as projected. As such, this gestural movement doesn't clearly reveal whether the gesture is iconic or metaphoric. The analysis of gestural movements in this study revealed 7 gestural movements were unclearly identified: two were produced by experts and 5 by novices. It shall be noted that these gestures were neither used for the calculation of the frequencies of gestural types nor used for the analysis relevant to the second research question in which the aim was to investigate the gestures that reveal a predicate.

To normalize the frequency of gestural types, the frequency of a particular gestural type was divided by the total number of instances of a gestural type that was produced in an explanation. This was done because gestures were classified based on their functions and some gestural movements had more than one function. Figure 7 presents an illustration of such a gestural movement. N4 produced a gesture that functioned as both iconic and deictic when explaining why the wax attached to the denser metal rod may melt faster. This example highlights how, given the context of speech, the gestural shape is representing iconically the shape of the metal rod while the movement from left to right is referring (deictically) to diagrams A and B as projected. Accordingly, this gestural movement is considered to function both as an iconic and a deictic gesture. Thus, dividing the gestural types by the total number of gestural movements would be misleading, since the total gestural types are more than the total gestural movements.



Speech	*It's more dense so the heat can, maybe it can gather more heat faster, the wax would melt faster than that one (a), the other one (b).*
Gesture	The palms of both hands are facing each other while being at distance from each other. Fingers are straight, close to each other, and pointing towards the screen. Hands are located at the right side of the body then moves to the left side of the body.

Figure 7: Illustration of a gestural movement that functioned as an iconic and a deictic gesture produced by N4 when explaining the difference in heat transfer in two different rods.

Results of the classified gestural movements are presented in Figure 8. Data analysis of the comparison of gestural types produced by experts and novices revealed some differences: The novices mostly produced deictic gestures (35.19%) while experts mostly produced metaphoric gestures (38.11%). A Chi-square test was conducted to determine if there were differences in the patterns of gestural types produced by novices and experts. Results revealed that the differences in the patterns of gestural types produced by novices and experts were significant (χ^2=21.919, df=3, $p<0.01$). Follow up analysis of novices' production of gestural types revealed their production of metaphoric gestures was significantly below the expected frequency while their production of deictic gestures departed significantly above the expected level ($p<0.01$). However, the detailed analysis of experts' gestural types reveals only the frequency of deictic gestures were significantly below the expected frequency ($p<0.01$).

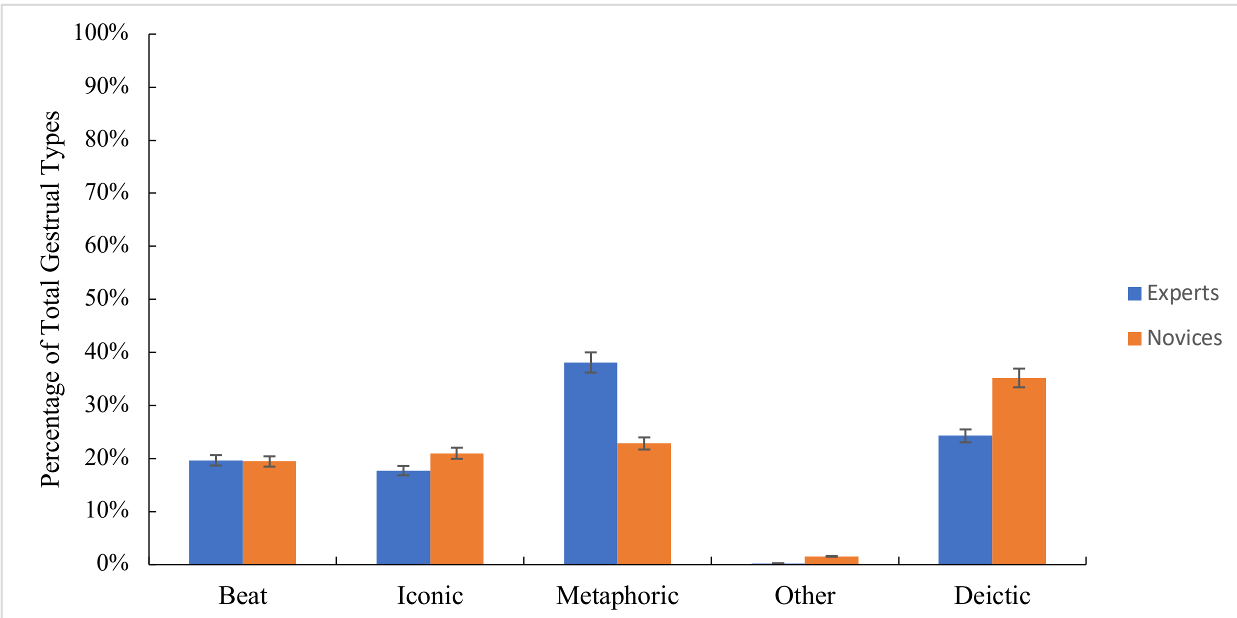


Figure 8: Total percentage of gestural types produced by novices and experts in all physics concept problems.

More specifically, data analysis for the types of the gestures produced by novices and experts distributed over the problem sets dealing with the different target physics concepts is presented in Figures 9, 10 and 11. The results revealed experts mostly produced metaphoric gestures in the heat, light and electric current problems. Specifically, they produced 35.06% metaphoric gestures in heat problems, 42.86% in light problems, and 36.44% in electric current problems. However, novices produced mostly deictic gestures in electric current problems (39.18%) and light concept problems (48.19%) while they produced mostly iconic gestures in heat concept problems (36.11%).

Three Chi-Square tests were conducted to identify whether the differences in the pattern of gestural types produced by novices and experts, across the different science concept problems (heat, light, and electric current) were significant. For heat concept problems, the patterns of gestural types produced by novices and experts differed significantly (χ^2=13.506, df=3, $p<0.01$). Specifically, in these problems, follow up analysis of novices' production of gestural types revealed their use of iconic gestures was significantly above the expected value ($p<0.05$) while their production of metaphoric gestures were significantly below the expected value ($p<0.1$). However, the analysis of experts' production of gestural types revealed their production of iconic gestures were significantly below the expected value ($p<0.05$) while their production of metaphoric gestures were significantly above the expected value ($p<0.1$).

As for light concept problems, results reveal the difference in the produced gestures among novices and experts was significant (χ^2=25.198, df=3, $p<0.01$). In these problems, follow up analysis of novices' production of gestural types revealed their use of deictic gestures was significantly above the expected value ($p<0.05$) while their production of metaphoric gestures was significantly below the expected value ($p<0.05$). However, the analysis of experts' production of gestural types revealed their production of deictic gestures was significantly below the expected value ($p<0.05$) while their production of metaphoric gestures was significantly above the expected value ($p<0.05$).

Finally, the analysis participants' production of gestural types in electric current concept problems revealed the difference in the pattern of produced gestures among novices and experts was significant (χ^2=12.533, df=3, $p<0.01$). In these problems, follow up analysis of novices' production of gestural types revealed their production of metaphoric gestures was significantly below the expected value ($p<0.05$) while their production of deictic gestures was significantly above the expected value ($p<0.05$). However, the analysis of experts' production of gestural types revealed their production of deictic gestures departed significantly above the expected value ($p<0.05$).

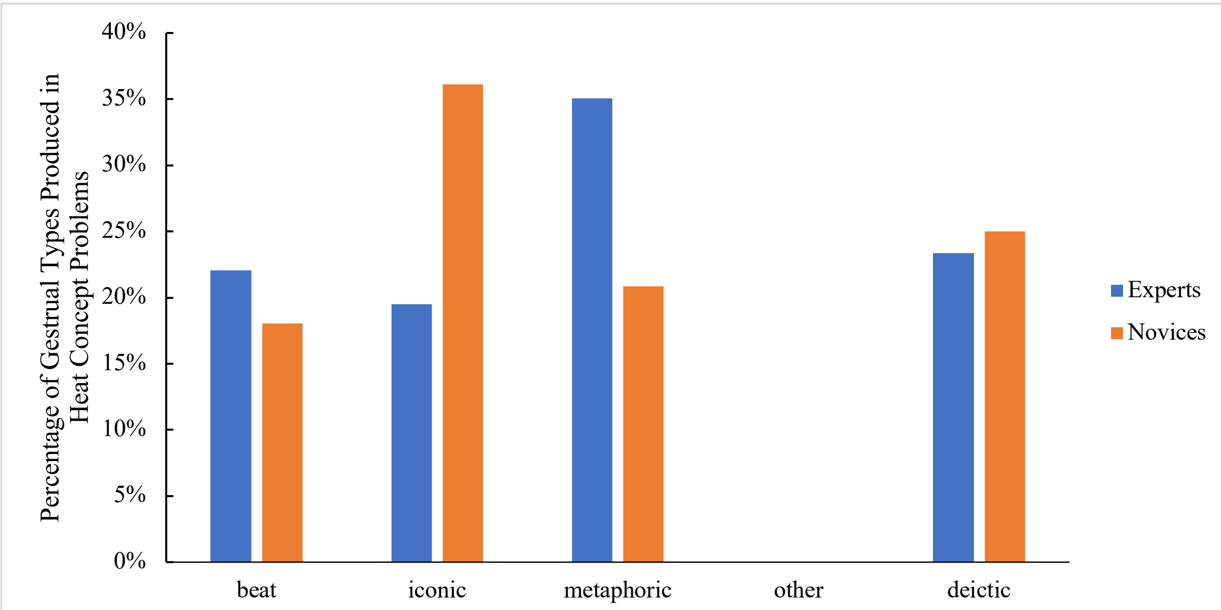


Figure 9: Percentages of total gestural types produced by novices and experts in heat problems

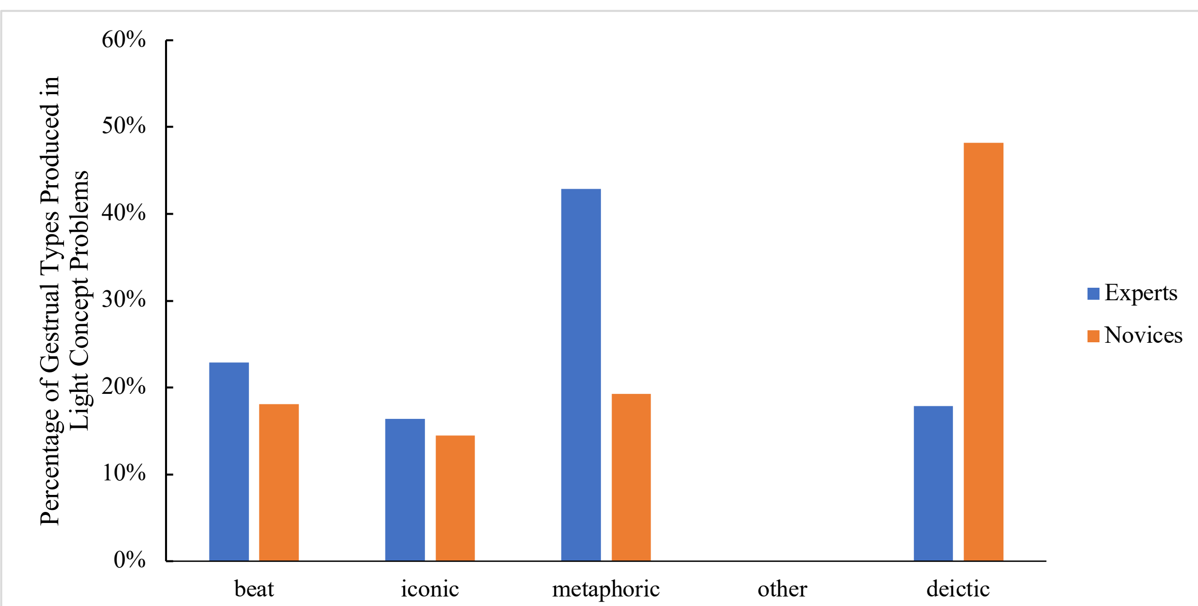


Figure 10: Percentages of total gestural types produced by novices and experts in light problems.

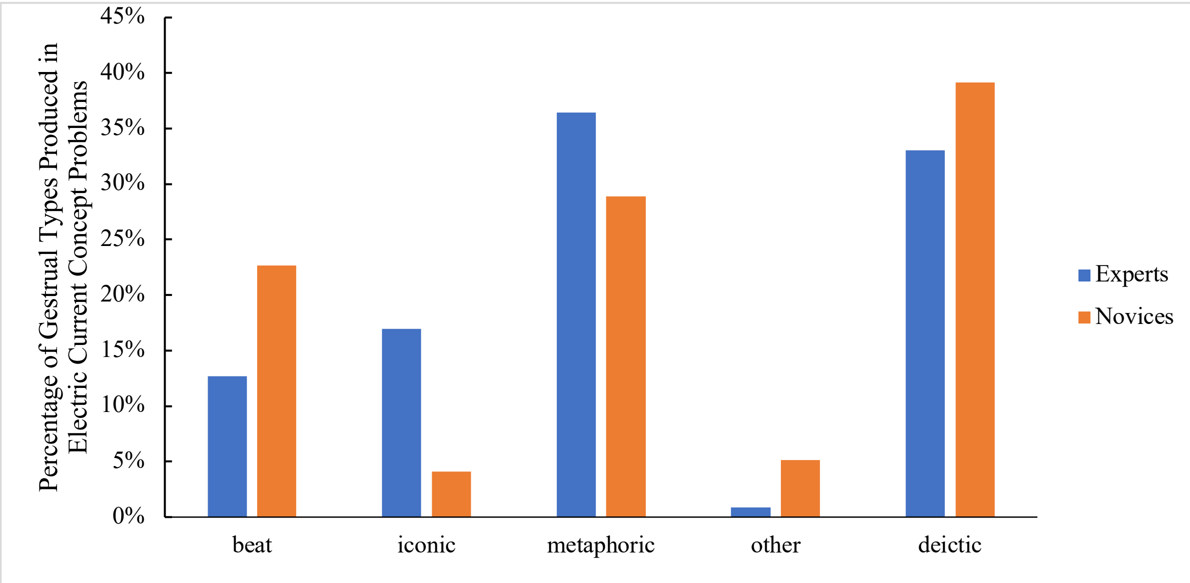


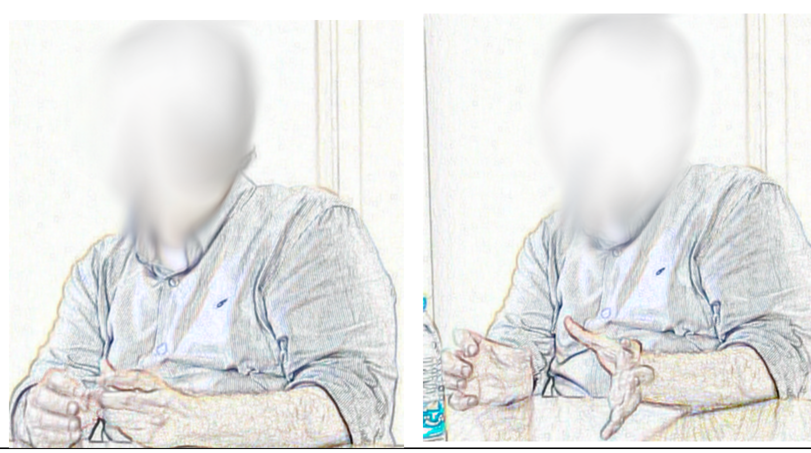
Figure 11: Percentages of total gestural types produced by novices and experts in electric current problems.

Second Research Question: Identification and Analysis of Gestural Predicates

Given that one of the purposes of this study was to explore whether gestures provide evidence of ontological categorization, the second research question aimed to determine whether the gestures produced when formulating science explanations reveal an ontological categorization or not. On that basis, the following section will elaborate how gestural predicates were identified. This section will also include a comparison of the gestural predicates produced by novices and experts across the three targeted science concept problem sets.

Identification of Gestural Predicates. The analysis of participants' gestures focused only on referential metaphorical gestures that are representing a metaphor targeting specifically heat, light and electric current concepts (refer for Chapter III for more details). For example, gesturing in a straight horizontal motion while saying "If it [ceramic] is an insulator then they both act as insulators -because you've sealed both of them" is considered as an iconic gesture that is representing how the mug is sealed/covered. This gestural movement didn't reveal an ontological categorization of a concept. However, gesturing in a horizontal straight movement while saying "there are some ceramics that actually <u>do allow the heat to go through</u>" reveals metaphorically construing heat as a substance that moves. Consequently, this metaphoric gesture enacts a matter predicate.

Furthermore, not all metaphorical gestures identified were predicating the three targeted science concepts. For example, Figure 12 below illustrates a metaphorical gesture produced by E1 when saying "the time taken for the actual voltage to discharge is a little bit longer." While saying "to discharge", E1 formed his hands in a grasp shape each facing the other; then, the hands are separated and expand in space in an outward motion away from each other. This gestural movement reveals metaphorically construing *voltage* as a substance that is contained. Consequently, this metaphorical gesture reveals an ontological categorization of the *voltage* concept and not electric current. As such, given the purposes of this study, this gesture was not considered in the analysis. Appendix G further presents illustrations for the gestural predicates produced by novices and experts and the challenges faced in analyzing them.



Speech	*The time taken for the actual <u>voltage to discharge</u> is a little bit longer*

Gesture	The palms of both hands are facing each other. Hands are slightly closed in a grasp shape. Then, the hands are separated and expand in space in an outward motion away from each other.
Figure 12: Illustration for E1 showing metaphorical gesture produced when explaining an electric current problem	

Following that, the analysis of referential metaphoric gestures aided in identifying a total of 166 gestural predicates: 112 gestural predications were produced by experts and 54 gestural predications were produced by novices. Then, novices and experts' gestural predicates were compared in terms of the total matter and process predicates produced in all science concept problems and distributed over the problem sets dealing with the different target science concepts (i.e., heat, light and electric current). Furthermore, a detailed comparison of the process predicates produced by experts in each problem sets dealing with the different target science concepts was conducted. Such comparisons helped in determining the extent to which novices and experts produced matter predicates and the extent to which the production of process predicates varied across the three targeted science concept problems: heat, light, and electric current.

Comparing Gestural Predications Produced. The analysis of gestural predicates produced in physics concept problems revealed that the majority of the predicates produced were matter predicates. Table 4 provides the overall percentages and frequencies of matter and process gestural predications produced by experts and novices across the three targeted concepts. Data analysis revealed 94.57% of the gestural predicates produced by participants, both novices and experts, were matter predicates and 5.42 % were process predicates. Specifically, all the gestural predicates produced by novices were matter predicates while 91.96% of the gestural predicates produced by experts were matter predicates and 8.03% were process predicates.

Table 4.
Overall percentages and frequencies of matter and process gestural predications produced by experts and novices across the three targeted concepts.

Participants	Matter Predicates		Process Predicates		Total	
	f	%	f	%	f	%
Experts	103	91.96	9	8.03	112	00.00
Novices	54	100.00	0	0.00	54	100.00
Total	157	94.57	9	5.42	166	100.00

The coding scheme developed by Slotta et al. (1995) was used to analyze gestural predicates. This analysis aided in identifying quantity, move, contain, block, supply, object, and absorb matter predicates from the coding scheme developed by Slotta et al. (1995). As for process predicates, only equilibration, movement, interaction, and systemwide predicates were identified (see Appendix G for illustrations of gestural predicates). Furthermore, as mentioned in Chapter III, the analysis of metaphoric gestures (and the identification of gestural predicates) was supported by the work on conceptual metaphors by Lakoff and Johnson (1980) and Johnson (1987).

The examples presented in Figures 13 and 14 are matter and process predicates that were identified by a novice and an expert participant following the theoretical framework of Conceptual Metaphor. For instance, the illustrated metaphorical gesture in Figure 13 is an example of a matter predicate produced by a novice participant (N2) when explaining how heat moves in a metal material. This metaphorical gesture was enacted by a straight horizontal movement. Notably, one of the discussed image schemas by Johnson (1987) was the Path schema which represents the movement of an object as having a starting point, a trajectory of movement, and an end point. This image schema reveals how an abstract concept is construed as an object/substance that has a linear trajectory and can be indicated by a moving hand tracing a line (Cienki, 2005). Based on that, the hand motion of N4 revealed metaphorically construing heat as a substance that moves. Consequently, this metaphoric gesture enacted the ‘move’ matter predicate.

Furthermore, the example illustrated in Figure 14 is of a metaphorical gesture enacting an equilibration, process predicate. This gestural predicate was evident as E1 produced a balance gestural movement. Based on the speech context, the balance up and down movement illustrated in the figure was analyzed as a gesture that reveals metaphorically construing heat energy as an equilibration process. This is so since one of the schemas discussed by Johnson (1987) was a Balance metaphor where a certain abstract concept is metaphorically construed as an object that is being balanced on a twin pan balance. Following that, the up and down hand motion reveals metaphorically construing heat/ energy as a quantity located on a vertical scale and the change in quantity is a change in location in space. But also, the coordination of the up and down movement of both hands revealed metaphorically construing energy as a physical balance between two objects with coordinated up and down movement. As such, this metaphorical gesture enacts an equilibration process predicate.

Speech	*If you have a metal material and you set it on fire using a lighter (b), it would all … the entire metal will start <u>catching up the heat</u> of this fire.*
Gesture	Hand moves in a straight horizontal movement.

Figure 13: Illustration of matter gestural predicate produced by N2 participant.

Speech	*So, there is no exchange of mass. <u>The only thing exchanged is energy between body A and B</u>*
Gesture	Hands -forming a grasp shape- move oppositely in an up and down movement.

Figure 14: Illustration of process gestural predicate produced by E1 participant.

More detailed analysis of the overall frequencies and percentages of gestural predicates produced by novices and experts distributed over the problem sets dealing with the different target science concepts are presented in Table 5. The detailed data analysis revealed no pattern of variation in novices' production of gestural predicates across the three problem sets targeting the science concepts heat, light and electric current. Notably, the comparison of gestural predicates produced by experts revealed the majority of the gestural predicates produced in the three science concept problems were matter predicates. However, there was a difference in the production of process predicates among experts depending on the targeted science concept. While the majority of the gestural predicates produced by experts in the three science concept problems were matter predicates, process predicates were only produced in light and heat concept problems. Specifically, 14.71% of the predicates produced when formulating explanations about heat were process predicates and 7.14% of the predicates produced when explaining light problems were process predicates. However, all the predicates produced when explaining electric current problems were matter predicates. Thus, the analysis of experts' gestural predicates revealed the extent to which experts produced process gestural predicates depended on the targeted science concept.

Table 5.
Percentages and Frequencies of Gestural Predicates Produced by Experts and Novices Distributed Over the Problem Sets Dealing with the Different Target Science Concepts

Science Concept Problem		Heat			Light			Electric Current		
		M	P	Total	M	P	Total	M	P	Total
Novices	f	21	0	21	17	0	17	16	0	16
	%	100.00	0.00	100.00	100.00	0.00	100.00	100.00	0.00	100.00
Experts	f	29	5	34	52	4	56	23	0	22
	%	85.29	14.71	100.00	92.86	7.14	100.00	100.00	0.00	100.00
Total	f	50	5	55	69	4	73	39	0	39
	%	90.91	9.09	100.00	94.52	5.47	100.00	100.00	0.00	100.00

Given that only experts produced process predicates, a more detailed analysis of experts' production of gestural predicates was conducted to examine the extent to which the production of process predicates varied among experts. Figure 15 provides the overall percentage of gestural predicates produced by experts distributed over the problem sets dealing with the different target physics concepts. The analysis of experts' gestural predicates revealed that E1 produced process and matter predications in heat concept problems: 31.25% were process predicates and 68.75% were matter predicates. However, E2 produced matter and process predicates only in light concept problems: 17.65% were process predicates and 82.35% were matter predicates. Similarly, E4 produced matter and process predicates only in light concept problems. Notably, all the gestural predicates produced by E3 reveal consistent use of matter predications. But all expert participants were consistent in their use of only matter predicates when explaining electric current problems. Thus, the evidence provided revealed differences among expert participants in their use of predicates in which the extent to which they produced predicates depended on the targeted science concept problems.

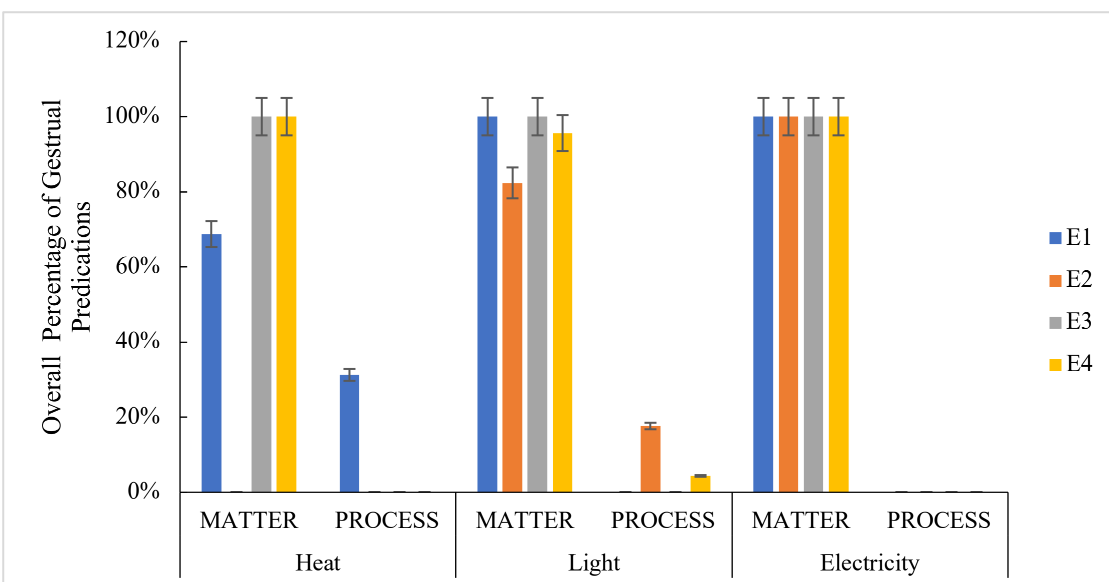


Figure 15: Overall percentage of gestural predicates produced by experts according to individual physics concept problem

Third Research Question: Analyses of speech predicates and concurrent gesture-speech pairs

The third research question aims to compare the gestural predicates of novices and experts - previously identified- to their speech predicates. This analysis addressed one of the purposes in this study which entailed exploring the extent to which novices and experts' ontological categorization was stable within an individual or change dynamically with context and across modality. To do so, this phase of analysis was composed of analyzing speech predicates and concurrent gesture-speech pairs. To analyze speech predicates, the speech analysis procedure developed by Slotta et al. (1995) was adopted. Slotta et al.'s study hypothesized that novices would use only matter predicates in both types of problems (science concept problems and material isomorphs) while experts would only use matter predicates in material isomorph problems and mostly use process predicates in physics concept problems. In this study, the analysis of verbal predications served as a replication of Slotta et al.'s study. This provided a test of the robustness of the original findings. Additionally, to compare gesture predicates to speech predicates, concurrent gesture-speech pairs had been analyzed to explore patterns of in/consistencies in the gesture and speech predications of novices and experts in all science concept problems and distributed over the problem sets dealing with the different target physics concepts

Replicating Slotta et al. (1995). This section presents the verbal data analysis upon adopting the same analytical procedure developed by Slotta et al. (1995). Appendix D provides examples of the verbal explanation data protocol of novices and experts. This appendix also explains how speech predicates were codded and the challenges faced in analyzing verbal data and how they were dealt with.

Multiple-choice responses. Participants' correct responses on multiple-choice problems are presented in Figure 16. Results revealed 28% of novices' multiple-choice responses were correct while 72 % of the experts were correct. Also, 67% of novices' multiple-choice responses in material isomorph problems were correct while 82% of experts' responses were correct. Notably, the analyses of experts' correct responses were analyzed case-by-case since they didn't always give the same answers. For instance, participant E1 when explaining heat transfer in Styrofoam cup and ceramic mug stated that ceramic mug insulates heat more than Styrofoam cup. However, other experts stated that Styrofoam insulates heat more than ceramic which is the correct response identified by Slotta et al. (1995). Following that, the response provided by E1 was considered correct especially as he had strong conceptual knowledge about heat. But also, the responses provided by other experts were considered correct.

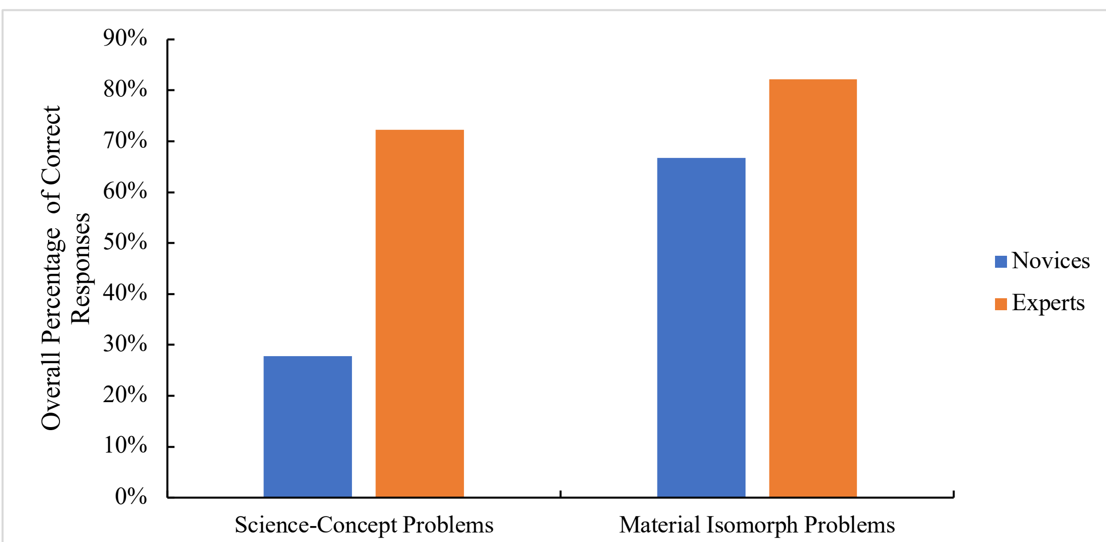


Figure 16: Overall percentage of novices and experts' correct responses in science concept problems and material isomorph problems.

Comparing verbal predicates in both types of problems. The analysis of speech followed the procedure developed by Slotta et al. (1995). Figure 17 presents results of speech analyses in both types of problems. Analysis of verbal predicates revealed that participants, both experts and novices, mostly used matter predicates in both types of problems. A detailed comparison of novices and experts' verbal predicates revealed differences in the use of predicates according to problem type: novices consistently used matter predicates in both physics concept problems and material isomorph problems; experts used a combination of matter and process predicates, with frequencies that depended on problem type. Specifically, 41.58% of the speech predicates produced by experts in physics concept problems were process predicates while 58.42% of the speech predicates were matter. However, 92.22% of the speech predicates produced by experts in material-isomorph problems were matter predicates. A two-way analysis of variance (ANOVA) was conducted to study the relation between speech predicates produced by participants (novices and experts) in both types of problems (science concept problems and material isomorph problems). The analysis revealed the variation in the speech predicates produced by novices and experts was significant $F(2, 18) = 50.06$, $p < 0.01$.

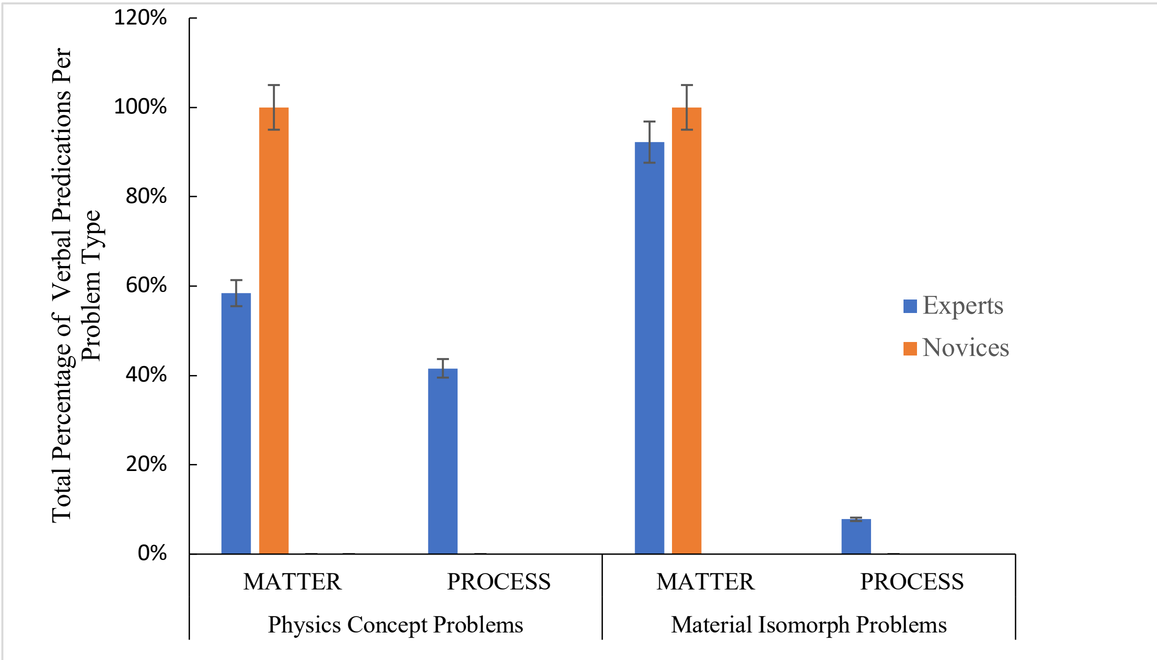


Figure 17: Total percentages of Matter and Process verbal predications produced by experts and novices in material isomorph problems and physics concept problems

Comparing verbal predicates across science concepts. The data analysis of speech predicates produced by both novices and experts distributed over the problem sets dealing with the different target physics concepts is presented in Figure 18. The analysis of verbal data for novices revealed they produced only matter predicates across the three physics concepts. However, experts used both matter and process predicates in all three physics concept problems, yet matter predicates were dominant in all three targeted concepts. Specifically, experts produced 51.61% process predicates in heat concept problems, 39.13% process predicates in light concept problems, and 33.33% process predicates in electric current concept problems (see Figure 18). The analysis revealed the variation in the speech predicates produced by novices and experts was significant $F\ (2, 9) = 20.329$, $p<0.01$. A closer look at the pattern of verbal predication reveal no variation in the use of process predicates by experts.

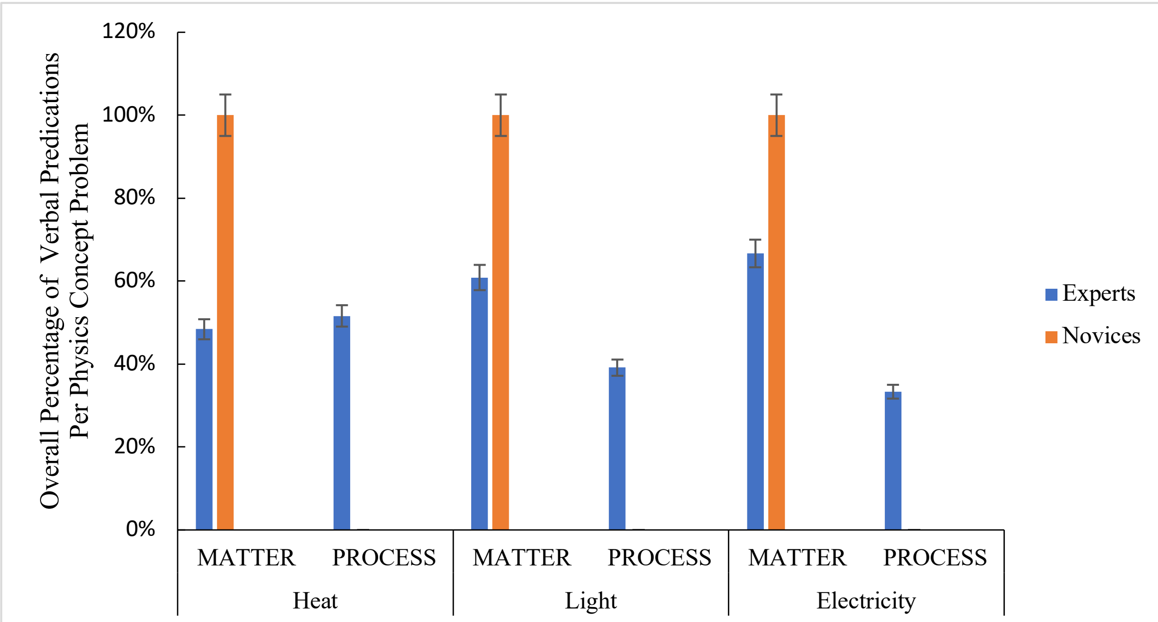


Figure 18: Overall percentages of Matter and Process verbal predications produced by novices and experts in individual physics concept problems

Analysis of Concurrent Gesture-Speech Pairs. In this sub-section, the results of the comparison of participants' gestural predicates to their speech predicates is presented based on the analysis of participants' concurrent gesture-speech pairs. Appendix H provides examples of consistent and inconsistent pairs and illustrates how concurrent gesture-speech pairs were analyzed and the challenges faced. In this study, a concurrent gesture-speech pair is an instance where a speech predicate has co-occurred with one or more gestural predicates. Three types of gesture-speech pairs were identified: inconsistent pairs, consistent matter pairs, and consistent process pairs. A consistent gesture-speech pair is evident when the speech and gestural predicates reveal the same ontological categorization, and it can be a consistent matter pair or a consistent process pair. For instance, the example illustrated in Figure 13 of the participant N2 presented earlier is considered as an example of a consistent matter pair. In this example, the analysis of verbal predication shows that the concept of heat was construed as a substance that is supplied by the lighter; that analysis of speech indicates a matter predication. The gesture produced showed that heat is construed as a moving substance, which indicates a matter predication. An example of an inconsistent gesture-speech pair is where the speech produced reveals categorizing the concept heat as a transfer process while the co-occurring gestural predicate reveal construing energy/heat as an object held in the hand (see Figure 26 in Chapter V).

Results of the analysis of concurrent gesture-speech pairs are reported in Table 6. The analysis revealed a total of 53 pairs were produced by expert participants and 27 by novice participants. Notably, all the pairs produced by novices were consistent matter pairs. However, there were three different types of gesture-speech pairs produced by experts: 60. 37% of the produced pairs were consistent matter pairs, 9.43% were consistent process pairs, and 30.19% were inconsistent pairs.

Table 6.
Frequencies and percentages of consistent matter pairs, consistent process pairs, and inconsistent pairs produced by experts and novices in physics concept problems

Concurrent Gesture-Speech Pairs		Experts		Novices		Total	
		f	%	f	%	f	%
Inconsistent Pairs		16	30.19	0	0.00	16	20.00
Consistent Pairs	M	32	60.37	27	100.00	59	73.75
	P	5	9.43	0	0.00	5	6.25
Total Pairs		53	100.00	27	100.00	80	100.00

Note: The table presents the overall frequencies of consistent matter (M) and process (P) pairs as well as inconsistent pairs.

More detailed data analysis of experts' consistent concurrent gesture-speech pairs is reported in Table 7. This analysis revealed that the majority of the pairs produced in individual science concept problems were consistent matter pairs. Analysis of the concurrent gesture-speech pairs revealed 83.33% of the pairs produced in heat concept problems and 84.21% of the pairs produced in light concept problems were consistent matter pairs. Notably, all the pairs produced in electric current problems were consistent matter pairs. Further analysis revealed variation among experts in the production of consistent pairs depending on the targeted science concept. That is, E1 produced consistent process pairs in heat concept problems only. However, E2 and E4 produced consistent process pairs only in light concept problems. Notably, E3 produced consistent matter pairs in all three concept problems. This reveals the extent to which experts' production of concurrent gesture-speech pairs were in/consistent depended on the targeted science concept.

Table 7.
Frequencies and percentages of Matter and Process consistent concurrent gesture-speech pairs produced by each expert according to individual physics concept problems

Physics Concept Problems	Consistent Predicates	E1		E2		E3		E4		Total	
		f	%	f	%	f	%	f	%	f	%
Heat	Matter	5	71.43	0	0.00	3	100.00	2	100.00	10	83.33
	Process	2	28.57	0	0.00	0	0.00	0	0.00	2	16.66
	Total	7	100.00	0	100.00	3	100.00	2	100.00	12	100.00
Light	Matter	3	100.00	5	71.43	2	100.00	6	85.71	16	84.21
	Process	0	0.00	2	28.57	0	0.00	1	14.29	3	15.78
	Total	3	100.00	7	100.00	2	100.00	7	100.00	19	100.00
Electric Current	Matter	3	100.00	0	0.00	1	100.00	2	100.00	6	100.00
	Process	0	0.00	0	0.00	0	0.00	0	0.00	0	0.00
	Total	3	100.00	0	100.00	1	100.00	2	100.00	6	100.00

Summary of Results Chapter

On the one hand, the analysis of speech revealed the production of verbal predicates depended on problem type where all participants only used matter predicates in material isomorph problems. In contrast, in science concept problems, novices only used matter predicates while experts used both matter and process predicates. Specifically, experts' use of matter and process predicates was evident in the three science concept problems but revealing no pattern of variability among experts.

On the other hand, the analysis of gestural predicates produced by all participants in science concept problems produced revealed variation in the gestural predicates produced by novices and experts. Novices produced only matter gestural predicates in all science concept problems, yet experts produced a combination of matter and process predicates, but with variation in patterns across experts and science concepts. Specifically, the production of gestural predicates by experts depended on the science physics concept problem (they produced a combination of matter and process predicates in heat and light problems while only matter predicates in electric current problems) and varied from one expert to another.

Notably, the analysis of concurrent gesture-speech pairs revealed that novices only produced consistent matter gesture-speech pairs. However, experts produced consistent matter pairs, consistent process pairs, and inconsistent gesture-speech pairs. The majority of the pairs produced by experts were consistent matter pairs, yet the production of inconsistent matter-speech pairs was evident in heat and light concept problems while only consistent matter pairs were produced in electric current problems. Finally, the production of consistent process pairs varied from one expert to another depending on the targeted science concept problems.

CHAPTER V

Discussion

This study addressed three research questions. The first research question aimed to identify participants' gestural movements, classify the gestures produced, and compare the gestures produced among novices and experts. The second research question aimed to explore whether gestures provide evidence of ontological categorization. Finally, the third research question aimed to explore whether ontological categorization is consistent within individuals across speech and gesture modalities. This chapter consists of four sections. The first section presents a discussion of the research findings organized by research question. The second section presents the limitations of the study then the third section discusses future recommendation while the fourth section discusses implications for both research and practice.

Discussion of Results

In this section, the results of the study will be discussed in relation to the relevant literature. This study addresses one of the disagreements among researchers in the field of conceptual change on how students (or generally novices) and experts categorize scientific concepts, namely, the ontological categorization of concepts and how the shift to greater expertise occurs. As such, this study involves, in part, a replication of the study conducted by Slotta et al. (1995) while adding gestures as an analytical lens. Eight participants were interviewed (four novices and four experts) during which participants were provided with multiple-choice problems similar to those provided by Slotta et al. (1995). The coding scheme developed by Slotta et al. was used for the analysis of speech and gestures. Specifically, the analysis of verbal explanations followed the same procedure developed by Slotta et al. (1995). However, the approach for analyzing gestures and determining gestural predications was developed based on prior research by McNeill (1992), Goldin-Meadow (2003), and Cienki (2010, 2016). It was further supported by the theoretical framework of Conceptual Metaphor developed by Lakoff and Johnson (1980) and Johnson (1987), drawing in particular on the underlying image schemas that ground conceptual metaphors.

Generally, the analyses revealed that participants produced various types of gestural movements that functioned differently. Notably, only the metaphorical gestures targeting the scientific concepts of heat, light, and electric current revealed an ontological categorization. Furthermore, the analyses of both speech and gestures provided evidence for the presence of inconsistent gesture-speech pairs: these represent instances where the speech predicate was different than the gestural predicate/s produced. This raise the question: To what extent do the study findings support the theoretical position proposed by proponents of the dynamic view of ontology versus the Ontological Shift theory?

The first sub-section in this discussion of results will discuss results relevant to addressing the first research question, highlighting the salient patterns of gestural types produced by novices and experts when formulating science explanations about heat, light and electric current. This discussion will further highlight how gestures may be considered as a conceptual resource produced by novices and experts to support formulating coherent explanations. The second sub-section will address how gestures provided evidence for novices and experts' ontological categorization. The value of using gestures as a window of ontological categorization will be discussed further, highlighting how gestural predicates were primarily spatial (which was not the case with speech), involving the use of various metaphors. The discussion will propose that ontological categorization involves a system of metaphorical construals. Finally, the last sub-section will compare the findings of this study with the study conducted by Slotta el al. (1995)

with focus on the degree of consistency between speech and gestural predications. The section will discuss this study's findings in relation to the disagreements existing between proponents of the Ontological Shift theory and dynamic view of ontology. The discussion will highlight findings that support proponents of both views but emphasizing the flexibility in novices and experts' ontological categorization. That sub-section will conclude by suggesting that the shift toward greater expertise (i.e., conceptual change) entails refinement as well as radical restructuring where various metaphors are coordinated differently leading to the construction of a process ontological category.

First Research Question: Analysis of the types of gestures. The first research question aimed to identify the gestural movements produced by novices and experts, to classify them based on their functions and to compare the gestural types produced by novices and experts. The following sub-sections will discuss results under two themes: the salient patterns of gestural types produced by novices and experts; and how gestures can be considered a conceptual resource that supports formulating science explanations.

Theme 1.1: Patterns of gesture types. The classification of gestural movements based on their functions revealed a broad pattern of variation among experts and novices. The analysis of gestural movements produced when formulating science explanations reveals that all participants gestured in the context of the problems dealing with all three targeted science concepts. Specifically, experts produced more gestural movements than novices in the three science concept problems.. Furthermore, classifying gestural movements based on their functions revealed variation among novices and experts in the types of gestures produced. The majority of the gestures produced by experts functioned as metaphors. However, the gestures produced by novices functioned mostly as deictic pointers when formulating explanations about light and electric current problems but were mostly iconic when formulating explanations about heat.

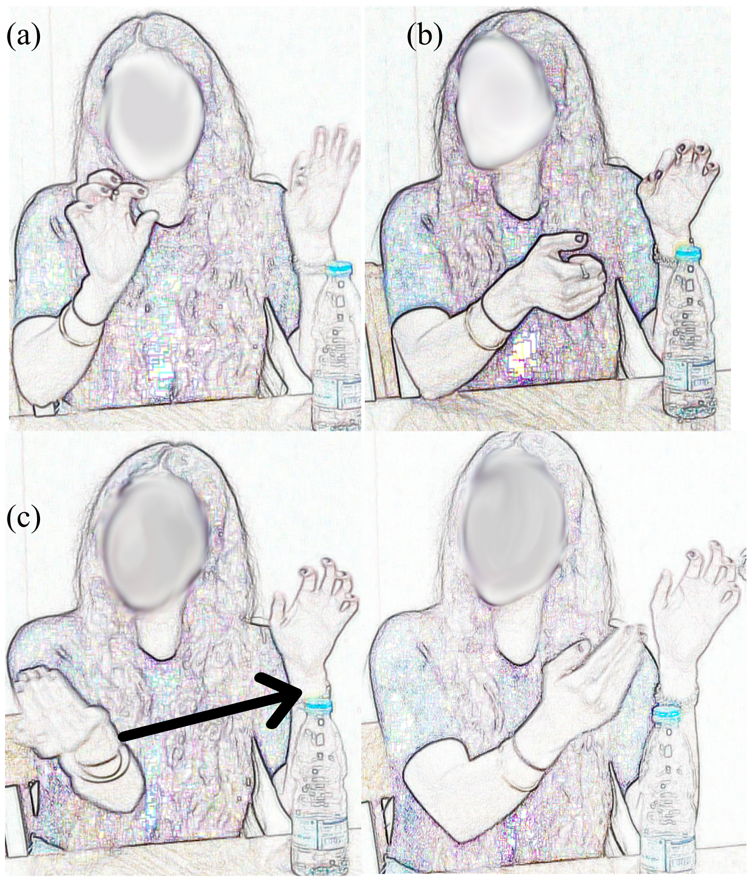
Prior research conducted on gestures has not documented the frequency of the gestural movements and types produced using a systematic, quantitative analysis of gestures. For instance, data presented by Dreyfus et al. (2015a), Roth and Lawless (2002a, c), and Scherr and colleagues (e.g., Daane et al., 2018, Scherr et al., 2013) were based on qualitative analyses of students and teachers/instructors' use of objects, computer simulations and drawings in the classroom. Specifically, the studies conducted by Roth and colleagues analyzed the types of gestures produced and their relation to speech based on the analysis of video recordings of students gesturing in science classrooms or in face-to-face interviews. In these studies, researchers provided a detailed analysis of the different gestures that students produce when learning science. Roth and colleagues suggested that as students are learning, they produce less gestures as they start relying more on the verbal modality. The researchers further added that learning may be accompanied by changes in the types of gestures (Givry & Roth, 2006; Roth, 2000, 2001; Roth & Lawless, 2002a, b, c), but these claims were not documented systematically through quantitative analysis of expert and novice use of gestures. In contrast, the studies conducted by Goldin-Meadow and colleagues adopted a quantitative, experimental methodology in analyzing the relation between gestures and speech and their impact on student performance on mathematics problems with an emphasis on representational gestures (deictic, iconic, and metaphoric). These studies focused on investigating children's mathematical understanding and thinking at different ages while reliably attributing meanings to the gestures produced and inferring the role of these meanings in mathematical thinking. One of these studies sought to determine the relation between gesture-speech mismatches and children's receptivity to instruction (Church & Goldin-Meadow, 1986). The conducted studies indicated that children who had gesture-speech mismatches were more receptive to instruction. But none of the prior conducted studies used a systematic, quantitative analysis of gestures across different levels of expertise.

The systematic, quantitative analysis of gestures in this study revealed variation in the pattern of gestural movements and types produced: as noted above, experts produced more gestural movements than novices; moreover, they mostly produced metaphorical gestures while novices mostly produced iconic gestures in heat problems and mostly deictic gestures in light and electric current. This varied pattern of production of gestural movements among experts and novices suggests that the production of gestural movements was evident when participants were formulating mechanistic explanations specifically in heat and electricity problems. These problems requested from participants to explain the movements of atoms or electrons. Furthermore, this varied pattern of production of gestural types among novices and experts aligns with the findings of an early study conducted by Chi, Feltovich, and Glaser (1981) which highlighted how novices and experts classified science problems differently. Specifically, Chi et al. (1981) found that experts classified science problems based on the underlying physical law while novices classified problems based on objects and surface characteristics of problems. These results align with the findings of this study because the metaphoric gestures, produced more frequently by experts, have abstract referents while iconic and deictic gestures, produced more frequently by novices, have concrete referents. This implies that experts' production of gestures revealed their use of abstract concepts in their explanations of problems, unlike the gestures used by novices which reflected concrete engagement with the problems.

Theme 1.2: Gestures as a conceptual resource. The previous discussion has highlighted a notable pattern of variation for the gestural types produced by novices and experts suggesting that experts used abstract science concepts in their explanation, unlike novices, who thought more concretely about the problems. This variation suggests that gestures may be considered a conceptual resource that participants drew on to support formulating science explanations. Prior studies have highlighted the resources that students and experts activate when formulating science explanations (e.g., diSessa, 1993; Givry & Roth, 2006; Hammer & Elby, 2003; Scherr, 2008). Specifically, Givry and Roth (2006) have argued - based on science classroom analysis of students' coordinated use of gestures and speech- how gestures are used by students as a meaning-making resource to help communicate their explanations. In addition, Scherr (2008) has noted that the production of gestures by students facilitates cognitive construction and helps them think clearly. In this study, participants used a variety of gestures, often more than one within a single explanation or even accompanying one phrase. These movements performed various iconic, deictic, and/or metaphoric functions and were often coordinated to produce a coherent explanation. The examples in Figures 19, 20, and 21 illustrate how three participants produced iconic, metaphoric, and deictic gestures when explaining the transfer of heat in two metal rods of different densities. Notably, these gestural movements were coordinated differently, but in each case supported formulating a coherent explanation. This is particularly interesting in cases where some participants' speech was unclear.

Figures 19 and 20 provide illustrated examples of the gestural movements produced by novices N2 and N4 when explaining heat transfer in two metal rods. Figure 19 includes an example that illustrates how N2 produced coordinated gestures to support her in formulating a coherent science explanation despite her speech being unclear. To elaborate, N2 supported her explanation of the heat problem using two gestural movements that functioned as iconic. These movements were representing the rectangular shape of the metal rod while the other movement enacted lighting the end of the rod using a match. Following that, she produced a straight horizontal gestural movement that functioned as metaphoric. This movement revealed a metaphorical construal of heat as a substance moving in the metal rod. Despite the mumbled, hesitant talk produced by the novice, the analysis of both speech and gestures provide a coherent explanation of the problem. Rather than saying precisely “metal rod”, she said vaguely “metal material” but accompanied that by the production of iconic gesture representing the shape of the metal rod. Furthermore, in her speech she does not articulate the idea that heat is moving along the metal rod, but this can be inferred from her gesture which enacted a spatial metaphor. As such, the overall analyses of N2’s gestures and speech reveal that she construed the lighter located at the edge of the metal rod as a source of heat that will heat-up the metal rod; this heat will eventually move along the metal rod until it reaches the end of the rod.

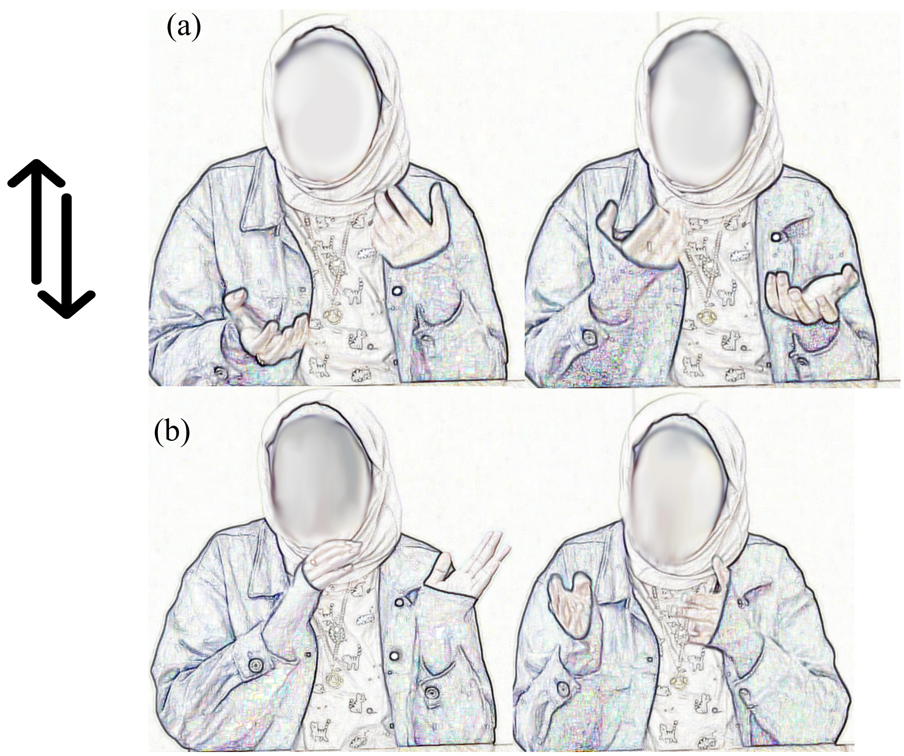
Another novice participant, N4, formulated a more complex explanation of how heat is transferred in the metal rod evident in both speech and gestures analyses (see Figure 20 below). The produced gestures varied in their functions and were coordinated to support formulating a coherent and more complex explanation than N2. Specifically, the metaphorical gesture produced by N4 suggests that heat was not construed as a moving substance; rather it is construed as a quantity that changes on a scale evident in her production of the balance gesture .The production of the metaphoric gesture was followed by a gestural movement that had both iconic and deictic functions, representing iconically the shape of the two metal rods and referring deictically to the problem projected. This suggests that the comparison of heat transfer in two metal rods was supported by iconic and deictic gestures. Consequently, the analyses of gestures and speech suggest that this participant was comparing the heat transfer in two metal rods that have different densities which affects the melting of the blob of wax. As such, these illustrations for two novice learners highlight how various gestural movements were coordinated differently, but in both cases, support the formulation of coherent science explanations.



Speech	*If you have a metal material (a) and you set it on fire using a lighter (b), it would all … the entire metal will start catching up the heat(c) of this fire.*
Gestures	(a) The index and thumb of both hands are distant from each other. Both hands move horizontally away from each other (b) The thumb of the left-hand closes and opens several times

	(c) The left hand moves in a straight motion from the extreme left side to the right side.

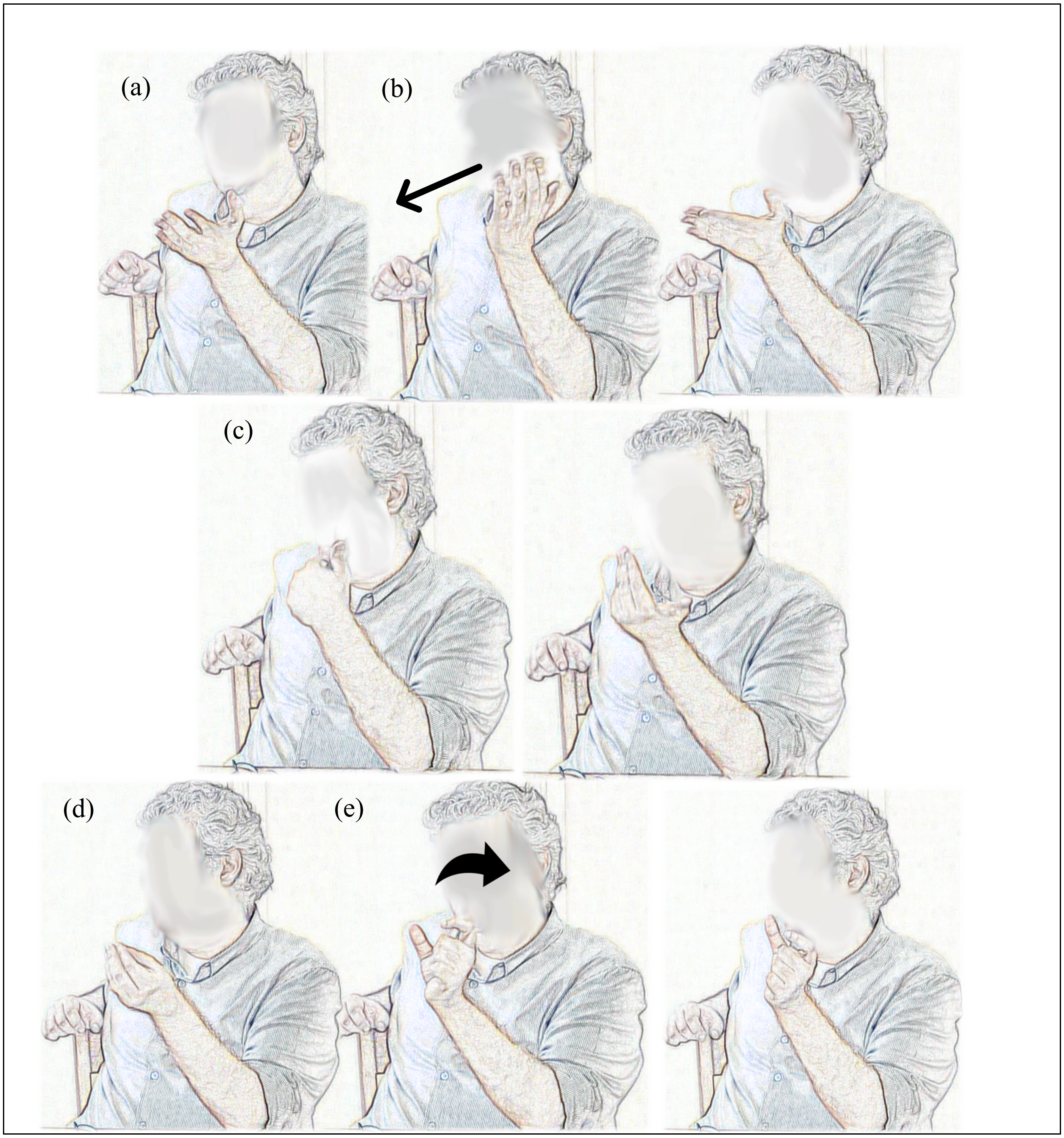
Figure 19: Illustration for N2 participant showing gestures produced when explaining a heat problem.



Speech	*It's more dense so the heat can, maybe it can gather more heat faster (a), the wax would melt faster than that one, the other one (b).*
Gestures	(a) Both hands move oppositely in balance up and down motion (b) Both hands are facing each other with a distance between them. Hands are located towards the right side of the body then moves towards the left side of the body.

Figure 20: Illustration of gestural movements produced by N4 participant when explaining the difference of heat transfer in two metals that have different densities.

Interestingly, an expert participant (E1) who had a strong scientific background relevant to understanding the concept of heat, formulated a more complex explanation when explaining heat transfer in two metal rods based on Newton's equation (law of heat transfer) (see Figure 21). This participant also produced various gestural movements that functioned as iconic, metaphoric, and deictic. Yet, these gestural types were coordinated differently to support the formulation of a complex, abstract explanation. Specifically, he first produced a deictic gesture to refer to the metal rod as projected. Also, he produced one iconic gesture that was representing the shape of the material and another three metaphoric gestures. The first metaphoric gesture was produced while saying "through the equation" in which the hand moved in a straight diagonal movement from the right side to the extreme lower left side. Then the hand rotates outwards from the wrist where the palm faces the ceiling and fingers are slightly bent. Unlike the metaphoric gestures produced by N2 and N4 participants, this straight, diagonal gestural movement doesn't reveal a construal of heat as a moving substance or as a quantity located on a scale. Rather this gestural movement is more complex since it reveals construing Newton's equation as a machine that has an input and an output; then, the hand rotation represents the 'output' of this equation (i.e. his gesture reveals the Functions Are Machines conceptual metaphor identified by Lakoff & Nunez, 2000). Finally, the third metaphorical gesture was produced when explaining the temperature difference between the material. This movement reflects metaphorically construing temperature as a quantity that is located on a scale and change of a quantity is a change in location. As such, the speech and gestures analyses for this expert suggests that he conceptualizes the conduction of heat in any metal material is determined by two quantities identified by Newton's law of heat transfer, which relates rate of heat transfer to thermal conductivity of the material and temperature difference.



Speech	*Basically, this is a metal (a), metal conducts heat and the form of heat is through the equation (b) Newtons equation in terms of the conduction of heat (c)so it depends on the thermal conductivity of the material (d) and the temperature difference (e).*
Gestures	(a) The palm of the right hand is facing up with the fingers straight and close to each other. The hand is pointing towards the screen. (b) The palm of the right hand is facing up with hand pointing towards the screen. Hand is located at the extreme right side then moves in a straight horizontal movement from the extreme right side towards the left side. (c) The palm of the right hand is facing up. Fingers are slightly bent and pointing towards the ceiling. Then, the hand rotates from the inside out. (d) The palm of the right hand is facing up with the fingers clustered toward each other. (e) The right hand has a fist shape except for the thumb and the index which are open with a distance between them. The hand is located at the center of the body. Then the hand rotates from the center towards the extreme right side (x2).
Figure 21: Illustration for E1 showing gestures produced when explaining heat problem	

Thus, this discussion highlights how three participants -two novices and one expert- produced various gestural movements of similar functions when explaining heat transfer. The analysis of both gestures and speech highlights how these gestures were coordinated differently to support participants in communicating coherent, and in some cases, complex science explanations. This suggests that gestures may be considered a conceptual resource that both novices and experts draw on when formulating science explanations.

Second Research Question: Gestures provide evidence of ontological categorization. The second research question aimed to explore whether the identified gestures provide evidence of ontological categorization. In this sub-section, I will discuss the value of using gestures as a window onto ontological categorization and discuss how predicates are represented through gestures. The results will be discussed under two themes: the value of using gestures as an analytical lens; and ontological categorization as a systemic construct.

Theme 2.1: The value of using gestures as an analytical lens. One of the aims in this study was to investigate whether the analysis of gestures provides evidence for ontological categorization. The analysis of participants' gestural types showed that not all gestural types revealed a predicate of an ontological category of the targeted scientific concepts; rather only metaphorical gestures revealed ontological predication. The gestures that didn't reveal an ontological category were iconic, deictic, and beat gestures as well as some metaphoric gestures that enact metaphoric construals of science concepts other than the target concepts heat, light, and electric current (e.g., voltage, temperature). The analysis of participants' gestures revealed the majority of the produced predicates were matter predicates. Novices only produced matter predicates through their gestures, while experts *mostly* produced matter predicates and their production of process predicates varied depending on the targeted science concepts.

The analysis of participants' gestural types highlights the value of using gestures as a window onto novices and experts' ontological categorization. The findings reported here suggest that gestures may be used as a window onto novices and experts' ontological categorization. It further highlights how gestural predicates are primarily spatial (in contrast to speech), involving the use of various metaphors. Moreover, the same gestural form may reveal different ontological categorization but also, a predicate may be represented spatially through different spatial forms. In addition, a new predicate was added to the coding taxonomy developed by Slotta et al. (1995). In the following sections I will illustrate and discuss each of these points.

The gestural predicates identified in this study were primarily spatial involving the use of various metaphors, unlike the speech predicates identified in the study conducted by Slotta et al. (1995) which varied across a wider range of meaning types. For instance, ‘quantity’ is a substance predicate identified by Slotta et al. (1995) that is used by some participants when formulating science explanations evident linguistically through words like *some*, *all*, *most, less*, *none of*, *lots*…etc. In this study, the quantity predicate was evident in phrases like ‘amount of heat’ or ‘more light’ phrases which reflect thinking of the targeted science concept as a substance-like entity that is quantified. Yet, quantity predicate had been enacted through an up and down hand movement orientation. Figure 22a provides an example of a metaphoric gesture that reveals construing light as a quantity *located* on a vertical *scale* where *more* light is located up and less light is located down and the change in this quantity represents a change in location in space. This suggests that quantity predicate can be enacted through an up and down hand movement orientation. Yet, the illustrations presented in Figure 22 highlights that quantity predicate can be also enacted spatially through an abrupt jumping movement towards and away from the body. Such variation in the spatial form of gestural predications is supported by the discussion provided by McNeill (1992) and Cienki (2005).

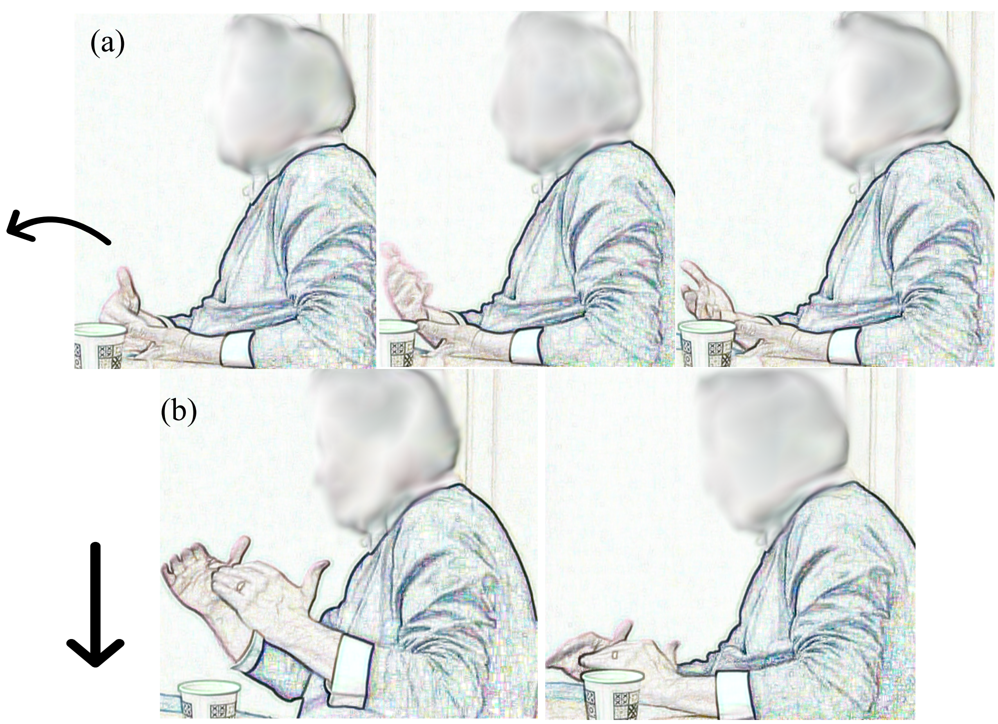
McNeill (1992) has highlighted nonlinguistic properties of gestures, including the idiosyncratic nature of gestures. He has explained that “gestures of different speakers can present the same meanings but do so in quite different forms" (McNeill, 1992, p. 22). Cienki (2005) has also noted that the variation in the physical form of metaphoric gestures may be due to the variation in the use of different embodied image schemas which can be mapped metaphorically onto the same target domain. As explained in Chapter 2, from an embodied cognition perspective abstract concepts are often understood metaphorically based on sensory-motor experiences, which is reflected in the use of Conceptual Metaphors (Lakoff and Johnson, 1980; Wilson, 2002). Lakoff and Johnson (2003) explain:

> "Just as the basic experiences of human spatial orientations give rise to orientational metaphors, so our experiences with physical objects (especially our own bodies) provide the basis for an extraordinarily wide variety of ontological metaphors, that is, ways of viewing events, activities, emotions, ideas, etc., as entities and substances." (p. 26).

The conceptual metaphors described by Lakoff and Johnson include many examples of different image schemas mapped on the same abstract concept. For example saying "I'm *in* love but we are *going* in *different* directions" reveals thinking of love as if physically contained at a specific location and as a journey.

This suggests that the variation in the spatial form of gestural predicates may be due to the variation in the underlying image schemas used as source domains in different conceptual metaphor. Examples of quantity predications revealed via gesture are illustrated in Figure 22 below in image (a) and (b). The illustrated examples are from participant E2. In Figure 22a we see that he produced a metaphoric gesture that reveals construing light as a quantity *located* on a vertical *scale* where *more* light is located up and less light is located down and the change in this quantity represents a change in location in space. Specifically, this gestural movement is characterized by a straight downward movement that embodies the Scale image schema. This schema is grounded on our experiences of piling up objects and having the level rise upwards

(Johnson, 1987). Notably, the metaphoric gesture produced by E2 illustrated in Figure 22b also represents the quantity predicate, yet the gestural form is characterized by an abrupt jumping movement towards and away from the body. Thus, this gestural movement reveals construing light as a quantity *located* on a linear *scale* where *more* light is located away from the body. This metaphoric construal embodies scale image schema, yet it is grounded on our experiences of moving away from objects: the more we move away from an object, the more the distance/ amount (Johnson, 1987). As such, the quantity matter predicate is enacted through various material substance metaphors which are represented in different spatial forms. These spatial forms instantiate image schemas that emerge from different physical experiences and interactions with the world (Cienki, 2005; Johnson, 1987).



Speech	*If your ambient light <u>is greater or equal,</u> then the ambient light…then you will not detect it. Then, the ambient light the <u>smaller it is</u>, the more the peak, the more you are able to detect whether the peak is coming from the bulb will be invisible, will be detectable*
Gestures	(a) The left-hand jumps in an outward arc movement (x2) (b) Hands are parallel to each other with the palm facing the table. Hands move in a downward motion

Figure 22: Illustration for E2 showing different gestural predicates produced when explaining light detection at day and night.

Finally, the value of using gestures as a window onto ontological categorization is further emphasized by identifying a matter predicate that was not identified by Slotta et al. (1995). The newly identified predicate is based on object schema which had been identified in the gestures produced in the study of Cienki (2005) where an abstract idea is referred to as an object that can be seen, held, and or felt. In this study, this gestural predicate represents metaphorically an abstract science concept as an object that is held in the hand which instantiates the bodily experience of holding objects, an experience that can't be expressed verbally. For instance, the illustration in Figure 23 is of participant E1 is an example of object, matter predicate produced when explaining the exchange of heat energy between two cubes due to temperature difference. In this example, the produced grasp hand shape reveals metaphorically construing heat energy as an object that is held in the hand which emerged from the physical experience of holding objects. Thus, this metaphorical gesture represents the matter predicate which reveals matter ontological categorization.

Speech	*There will be exchange of energy but not mass.*
Gesture	Both hands form a grasp shape.

Figure 23: Example of object, matter predicate produced by an expert.

In sum, this discussion highlights how gestural predicates are represented spatially in ways that differ from speech. These gestural predicates are represented spatially through metaphors. The variation in the physical form of gestural predicates among participants may be due to the variation in the embodied image schemas emerging from physical experiences and mapped onto abstract concepts metaphorically.

Theme 2.2: Ontological categorization as a systemic construct. The very fact that gestural predicates are represented spatially involving the use of various metaphors poses a question of how ontological categories are represented. The last sub-section discussed how gestural predicates are enacted through different spatial metaphors. In this sub-section, I would like to discuss the implications of the same gestural form may play a role in different ontological categorizations depending on the way that metaphors are coordinated. This point will be illustrated by comparing a gestural predicate produced by a novice participant (N4) and an expert participant (E1), who has a strong scientific background relevant to understanding the concept heat. The illustration in Figure 20 is of participant (N4) is an example of a balance gesture produced when explaining how heat is gathered more in the denser metal rod. This gesture reveals metaphorically construing heat as a quantity located on a vertical scale where more heat is located up and less is down and change in quantity is a change in location in space. Thus, this gesture represents the quantity predicate which reveals matter ontological category. However, the example illustrated in Figure 23 is of an expert participant (E1) who produced a balance gesture when explaining thermal equilibration. This hand movement embodies both Balance and Scale image schemas. Specifically, the hand movement reveals metaphorically construing thermal equilibration as the coordinated up and down movement on two vertical scales: Two *quantities* located on a scale and the coordinated changes in these quantities are the coordinated changes in location in space. Furthermore, the *balance* gesture reveals that thermal equilibrium is construed as the physical balance of two objects being on a scale. As such, this gesture is analyzed as an equilibration process predicate that is enacted using a variety of spatial metaphors.

Speech	*One is hotter so the heat will go from the higher to the lower until they reach equilibrium and they will have same temperature*
Gestures	Both hands are located above the table at the center. Palms are facing down. Hands move oppositely in an up and down motion.
Figure 24: Illustration from E1 showing a balance gesture when explaining thermal equilibration.	

The point here is that the equilibration process predicate is enacted through both Balance and Scale image schemas while the quantity matter predicate is enacted by only Scale image schema. The Scale image schema is common in both. Therefore, gestural predicates are represented spatially through various metaphors, yet depending on how these metaphors are coordinated, a different ontological category is constructed. From this perceptive, it might be better to view ontological categorization as a systemic construct – i.e. ontological categorization involves a system of metaphoric construals where different conceptual metaphors are activated and coordinated revealing the construction of an ontological category for a particular science concept.

Third Research Question: Consistency between speech and gesture predications. The third research question addressed the consistency between speech and gesture predications. Addressing this issue involved replicating Slotta et al. (1995) where the analyses of speech predications from the replication were compared with the analyses of gesture predications. The following sub-sections will first discuss participants' speech predicates from this study in comparison to the speech analysis of Slotta's et al. (1995) study. Then, the second section will discuss the analysis of participants' concurrent gesture-speech pairs which suggest the presence of flexibility in participants' ontological categorization. Finally, this section will conclude by discussing the current study findings in relation to the disagreement existing between proponents of both views, proponents of the Ontological Shift theory and the dynamic view of ontology, on the extent to which the shift toward greater expertise (i.e., conceptual change) entails refinement versus radical restructuring. The results will be discussed under the following themes: Comparison of Speech Analysis with Slotta et al. (1995), Analysis Of Concurrent Gesture-Speech Pair Reveals that Flexibility is a Sign of Expertise, and Conceptual Change Entails Radical Restructuring and Refinement.

Theme 3.1: Comparison of current study's speech analysis with Slotta et al. (1995). This study involves, in part, a replication of the study conducted by Slotta et al. (1995) while adding gestures as an analytical lens. The reported results of the current study findings are to a certain extent different from those of Slotta et al. (1995). Specifically, the analysis of multiple-choice data in Slotta et al. (1995) revealed that experts answered correctly all science concept problems, while novices responded to almost half of the problems correctly. However, both novices and experts answered nearly all the isomorph problems correctly. In contrast, the analysis of multiple-choice data in this study revealed only 82% of experts' responses were correct while 28% of novices' responses were correct when solving science concept problems. This suggests the presence of variation in expert participants' responses compared to that of Slotta et al. may be due to greater variation in experts' conceptual background in science in this study (see Appendix C for more information on participants recruited in this study).

The analysis of speech predicates from the study conducted by Slotta et al. (1995) revealed that novices' use of matter predicates didn't depend on problem types since they used only matter predicates when explaining both types of problems (science-concept problems and material isomorph problems). However, the analysis of experts' explanations revealed the use of process predicates in explaining science concept problems and on matter predicates in explaining material isomorph problems. In contrast, in this study the analysis of speech predicates reveals that novices used matter predicates in both types of problems while experts used *mostly matter* predicates in science concept problems and only matter predicates in material isomorph problems. The use of matter and process predicates was evident in the three targeted concepts.

The former discussion provides evidence supporting the theoretical position held by proponents of the dynamic view of ontology. The analyses of speech predicates in this study revealed variation among experts in their production of correct responses in addition to their frequent production of matter predicates. On the one hand, the studies conducted by Chi and colleagues suggested that the development of expertise is evident in the *frequent* use of process predicates. Accordingly, researchers proposed that novices categorize science concepts within the matter category while experts think of science concepts as a process. On the other hand, Gupta et al. (2010) argued by drawing on previous research and on a qualitative case study analyses against Chi's and colleagues' theoretical position. The researchers have argued that learners and experts don't categorize science concepts into one category (Gupta et al., 2010). Rather, they proposed that both novices and experts productively and flexibly invoke multiple ontologies which reveal that "our conceptual knowledge organization is likely to be network-like rather than hierarchical." (Gupta et al., 2010, p.27). Notably, the findings reported here in this study from the speech analyses suggests that ontological categorization of science concepts is not hierarchal as proposed by Chi and colleagues. First, the analysis of speech predicates reveals that both novices and experts frequently produced matter predicates. This suggests that novices and experts' ontological categorization can't simply be hierarchal and marked in the frequent production of either matter or process predicates. Second, the reported findings in this study for the presence of variation in experts' formulation of correct responses suggests varied levels of expertise among experts across the different science topics. Thus, the former discussion suggests ,probably, the shift toward greater expertise is more complex than Chi and colleagues have proposed.

Theme 3.2: Analysis of concurrent gesture-speech pair reveals that flexibility is a sign of expertise . The analyses of gestures and speech predicates aided in the identification of gesture-speech pairs. The analysis revealed that novices only produced consistent matter gesture-speech predication pairs. In addition, the majority of the pairs produced by experts were consistent matter predication pairs. However, experts also produced some inconsistent pairs in the context of heat and light concept problems while all speech-gesture predication pairs produced in electric current problems were consistent matter predication pairs. Experts produced some consistent process speech-gesture predication pairs, but this varied from one expert to another and depended on the targeted science concept problems.

The discussion of this section will focus on the instances of production of inconsistent gesture-speech pairs by experts. These instances provide evidence for the presence of flexibility in the use of predications which may be considered a sign for expertise rather than its lack. This is because the production of these pairs represents an instance where a speech predicate has co-occurred with more than one gestural predicate and each predicate may be depicting a meaning itself from a specific lens. This supports the theoretical position held by proponents of the dynamic view of ontology.

To elaborate, one of the challenges faced in the analyses of gestures and speech predications lies in determining whether a particular concurrent gesture-speech pair reveals *either* matter *or* process ontological category. Notably, the current study findings align with that conducted by Goldin-Meadow and colleagues. Specifically, Goldin-Meadow (2003) provided evidence of gesture-speech mismatches when analyzing children's responses on some of Piaget's class tasks (e.g. number conservation): A gesture-speech mismatch is an instance were the meaning conveyed by the speech is different than that conveyed by gestures. Interestingly, children who exhibited gesture-speech mismatches were more receptive to instruction than their counterparts (Congdon, Novack, & Goldin-Meadow, 2018; Goldin-Meadow, 2003). The point here is that the evidence elaborated by Goldin-Meadow on gesture-speech mismatch is indicative for student's receptivity to instruction. However, in the study reported here, the production of inconsistent gesture-speech pairs suggests the presence of flexibility in experts' ontological categorization which supports the theoretical position held by proponents of the dynamic view of ontology.

Scherr, Dreyfus and other colleagues have argued how the energy concept is thought about differently based on context suggesting flexibility (Dreyfus et al., 2014; Dreyfus et al., 2015a; Scherr et al., 2012). For instance, Dreyfus et al. (2015a) have provided evidence where novices and experts inconsistently used matter and process predicates when learning the concept energy. The researchers stated:

> Expertise in physics is not constituted in learning a single canonical way of reasoning about a concept or ontologically categorizing that concept; rather, it is constituted in coordinating multiple metaphors and ontological categories to flexibly understand and apply that concept in different contexts." (Dreyfus et al., 2015a, p.834).

This discussion aligns with the theoretical position proposed by Dreyfus et al. but also, the findings from this study regarding the presence of inconsistent concurrent gesture-speech pairs suggests that the gestural predicates produced provided a perspective complementary to that of speech. For instance, the example in Figure 23 illustrates E1's use of an inconsistent speech-gesture predication pair. In that example, while the analysis of speech revealed an equilibration process predication, the concurrent gestures indicated a move matter predicate and an equilibration process predicate. A more specific finding was that inconsistency varied among expert participants depending on their area of specialization. For instance, the production of inconsistent pairs by E1 was only evident in heat problems, an area in which he, as an engineering specialist, has a great deal of expertise. Another expert, E2, only produced inconsistent pairs in the light problems. Again, it is interesting to note that this is a domain in which E2, as a physicist, would be expected to be particularly knowledgeable in. Therefore, inconsistency in speech-gesture predications seem to be more an indication of the skilled flexible use of resources by an expert rather than a sign of the lack of expertise.

Theme 3.3: Conceptual change entails radical restructuring and refinement. In line of the above, this study addresses one of the disagreements existing between proponents of the dynamic view of ontology and Ontological Shift theory on the extent to which ontological categorization is stable or dynamic and how the shift to greater expertise occurs. The former discussions have elaborated on results emerging from gesture and speech analyses in an attempt to reinterpret the debate existing between proponents of both views. Notably, the adoption of gesture and speech analyses highlights large grain size changes in ontological categorization occurring with the acquisition of expertise. It further highlights the nature of flexible and dynamic use of ontological predications at a finer level of detail. Specifically, the following sections will argue how, through gesture and speech analyses, the shift towards greater expertise (i.e., conceptual change) entails refinement as well as radical restructuring where various metaphors are coordinated differently leading to the construction of a process ontological category.

To elaborate, the analysis of speech reveals large grain size changes in ontological categorization occurring with the acquisition of expertise. That is, the findings reported here in this study on the analysis of participants' speech reveals that novices *do* conceptualize science concepts as matter while experts as a constrained-based process. Slotta et al. (1995) have defined a constrained-based process as a:

> special type of process in which a defined system (e.g., an electric circuit) behaves according to the principled interaction of two or more constraints (e.g., the voltage at different points in the circuit). These principled interactions typically correspond to physical laws of nature, such as Ohm's law, Newton's second law, the laws of thermodynamics, or Maxwell's equations. (p. 377)

The analysis of multiple-choice responses for experts reveal that most of the experts have verbally explained the science concepts as a process that is constrained by a principled interaction as defined by Slotta et al. (1995). For example, one of the participants articulated:

> They [ceramic mug and Styrofoam cup] are definitely less hot than they were before. That's the only thing I can confirm. But again, if you tell me that the ceramic is an insulating material, then I would tell you that both will be as hot as each other depending again on the conduction of heat through. This is the heat equation for the conduction, which is basically Q equal to change in temperature, multiplied by area, multiplied by conductivity.

The former example highlights how an expert explained heat as a process that is governed by the equation of thermal conductivity. On that bases, it is suggested that conceptual change entails radical restructuring as learners have to shift their thinking of science concepts from the matter category to the process ontological category evident in the language used. This supports the theoretical position held by Chi and colleagues where learners have to develop a new conceptualization of science concepts. However, a more detailed analysis of experts' explanations reveals matter conceptualization has been *embedded* in their explanations. That is, there are instances where material substance words were used when explaining science concepts as a constrained-based process. For instance, the previous example of E1 reveals how material substance phrase (heat go from...to...) was used when explaining heat as an equilibration process. Slotta and Chi (2006) have addressed this issue by stating “physics experts do maintain substance-based conceptualizations in parallel with their more normative process-like views.” (p. 266). Henderson et al. (2017) further suggested: “Experts may indeed use expressions that suggest an ontological miscategorization, but do so with full awareness that their usage of terms and predicates do not align ontologically (e.g., for instructional purposes).” (p. 30).

Notably, further analysis of experts’ verbal explanations reveal matter conceptualization is embedded in process predicates despite that experts frequently used matter predicates. This supports the position held by proponents of the dynamic view of ontology. Hammer et al. (2011) argued the use of matter phrases shall not be treated as statistical noise. Rather the use of such phrases supports explaining abstract concepts as a process: They are a conceptual resource that experts invest in to support explaining science concepts as a constraint-based process. From that perspective, the use of matter predicates -which reflect the use of metaphors- can’t be considered as constraining novices’ learning knowing that experts have used them as well. In sum, the analysis of speech reveals how experts explain science concepts as a constrained-based process while novices as a material substance. This highlight large grain size changes in ontological categorization occurring with the acquisition of expertise, and that novices are limited to a material substance ontology. However, matter conceptualization was embedded in experts’ explanations. This suggests -based on speech analyses- that the shift to greater expertise entails shifting learners’ ontological categorization from the matter category to the process category while building on their material conceptualization of abstract science concepts.

Despite that the analyses of speech reveal large grain size changes in ontological categorization, the analysis of gestural predicates fine grain changes occurring with the shift to greater expertise. This suggests that conceptual change entails refinement and building on learners' conceptual resources to construct process ontological category; thus, supporting the theoretical position held by proponents of the dynamic view of ontology. Researchers using Conceptual Metaphor theory as a window onto science leaning highlighted that metaphors are among the resources that both novices and experts invest in. (e.g., Amin, 2009; Jeppsson et al., 2013, and Jeppsson et al., 2015). For instance, Jeppsson et al. (2015) compared novices (undergraduate students) and experts' (PhD students) use of conceptual metaphors when solving physical chemistry problems. The study revealed that the shift to greater expertise is evident in learning how to coordinate the appropriate metaphors implicit in the language of science. In similar vein, the findings reported here in this study, suggests that shifting learners' ontological categorization from the matter to the process category entails refinement and reorganization of metaphors to support the construction of process ontology.

For instance, the balance gestural movements produced by E1 (see Figure 23) and N4 (see Figure 20) reflected the coordination of various spatial metaphors. Both E1 and N4 produced the same gestural form and metaphorically construed heat as a quantity located on a vertical scale. But also, construing heat as an equilibration process by E1 was grounded on construing it as a quantity. This suggests that thinking of heat as a quantity may be considered as a resource that support thinking of abstract science concepts as a process. As such, the analysis of gestural predicates in the current study suggests that changing learners' conceptions entails *refinement* and building on their knowledge of heat being construed as a quantity to support thinking of heat as an equilibration process. This reflects the presence of continuity between learners and expert scientists (Amin, 2009). As such, the former discussion suggests a flexible and dynamic use of ontological predications at a finer level of detail.

In sum, the analyses of both speech and gestural predicates suggests an intermediate perspective onto how the shift to greater expertise occurs building on the position held by proponents of the Ontological Shift theory and the dynamic view of ontology. The analysis of speech suggests that a coarse level of developing scientific expertise does involve starting to conceptualize some science concepts as a constrained-based process, and that novices are limited to a material substance ontology. Therefore, this study does provide some evidence in support of the Ontological Shift view proposed by Chi, Slotta and colleagues. However, as discussed above, a finer grain size of analysis of including close attention to gestures and the coordination between speech and gestures reveals ontological categorization is a more systemic construct that Chi and colleagues have not acknowledged: it is a system where various metaphors are enacted and coordinated leading to the construction of an ontological category. Viewed in this way, the evidence also provides some support for the position held by proponents of the dynamic view of ontology where novices and experts' ontological categorization involves the coordination of a variety of conceptual resources (including metaphors enacted by gestures).

Recommendations for Future Research

This study and the discussion above raise a number of open questions for future research. One proposed issue is exploring the dynamic nature of novices and experts' ontological categorization using different study design context. This raises the question of the nature of novices and experts' ontological categorization and the extent to which it is dynamic in naturalistic contexts. Another issue is the influence of expertise level of the participants recruited when exploring the nature of ontological categorization across different science topics. This raises the question for future research to explore the changes in ontological categorization of concepts as learners acquire expertise at a specific science topic. Finally, the last raised issue is exploring the nature of ontological categorization while using different kinds of problems. This raises the question of the kinds of tasks and problems provided for participants in future research when exploring the nature of ontological categorization. Thus, the proposed recommendations for future research lie in further exploring ontological categorization of novices and experts using different design contexts, recruiting participants off different expertise, and providing participants with different tasks.

To elaborate, the first recommendation for future research is the need to conduct more research that further explores learners and experts' ontological categorization in naturalistic contexts using the systematic analyses of language and gestures. The design of the study reported here was necessarily influenced by the prior work of Slotta et al. (1995) since it was partly a replication of that study. Therefore, ontological categorization was explored by providing novices and experts with multiple-choice problems and asking them to formulate explanations of the phenomena. Furthermore, the systematic, quantitative analysis of gesture in this study was motivated by Nünez's (2015) critique of the qualitative case study conducted by Dreyfus et al. (2015) in naturalistic setting. This kind of systematic, quantitative study adopted in this study was needed to evaluate the value of using gestures as a window onto ontological predication. However, this study has only just begun to examine the role of gestures (alongside speech) as a resource for ontological categorization. Further research is needed that would explore novices and experts' ontological categorization in naturalistic contexts. Specifically, more research is needed to help in further identifying the kinds of gestures (and other) resources that are activated and coordinated, the extent to which large grain size changes in ontological categorization occur with the acquisition of expertise and the nature of flexible and dynamic use of ontological predications at a finer level of detail.

A second recommendation for future research lies in exploring patterns of ontological categorization across a number of different levels of expertise. Although this wasn't systematically explored in this study, the experts recruited for this study did in fact vary in their specific areas of expertise and this seemed to impact the way in which they engaged with the problems. For example, the results suggested that process predications were produced in the context of problems dealing with concepts more central to their area of expertise. So while this study was designed to compare experts and novices' ontological categorization, finer distinctions were needed to make sense of some the results. Therefore, it is recommended that future research recruit participants that have expertise at a number of different levels, including for example an intermediate level of expertise such as undergraduate or even graduate students majoring in the sciences. Moreover, it might be more appropriate to define the scientific topics explored more narrowly. Thus, it would be important to conduct a study that could help in exploring the changes in ontological categorization of concepts as learners acquire expertise over a series of levels of expertise within a specific scientific topic.

Finally, a third recommendation for future research is to explore novices and experts' ontological categorization using problems and tasks that elicit *explicit* ontological categorization. The results in this study are based on providing participants with multiple-choice problems that require the participant to formulate science explanations. The analyses of speech and gestures were used to infer the ontological predications made by the participants. But participants were not explicitly asked whether they consider particular science concepts to belong to particular ontological categories. It is noteworthy, that the study conducted by Slotta et al. (1995) was grounded in the work of Keil (1979) which proposed that knowledge is hierarchically represented in the mind in the form of a tree-like system of ontological categories. However, as noted by Amin (unpublished manuscript) this was based on providing participants with tasks that required *explicit classification* of everyday concepts such as objects, artifacts, animals…etc. Amin notes that Keil's methodology carefully insured that when participants made predication judgements they avoided the use of metaphors in their judgements. In contrast, Slotta et al. (1995) elicited *implicit* categorization of science concepts and the explanations produced were full of implicit metaphors. The analysis of the study reported here drew explicitly on the conceptual metaphor framework. This might explain why more matter predications were identified than in Slotta et al.'s study. Future research will need to distinguish implicit and explicit ontological categorization and attend more closely to the role of metaphors. The study currently conducted by Amin (unpublished manuscript) is exploring this issue.

Implications

This study has direct implications for theories of science concept learning and consequently has implications for improving the design of effective learning environments. Indeed, the importance of theory formation to the design of instruction had been highlighted by diSessa and Cobb (2004). The use of gestures as an analytical lens onto ontological categorization helped in further understanding the nature of novice learners and experts' conceptions. Specifically, the current study helped in exploring what learners' conceptions look like as they enter the classroom and how the shift to greater expertise occurs. While the study doesn't directly address pedagogical and instructional implications, it does provide a better understanding of the nature of learner conceptions, the underlying difficulties faced in learning some science concepts, and the conceptual resources that learners and experts invoke when formulating science explanations. The results provide the basis for developing a better understanding of learners and experts' thinking in a complex real-world learning setting that involves the coordination of various resources (e.g., speech, visual representations, gestures, and others). These theoretical developments, in turn, suggest improvements of the design of instruction. The following sub-sections will further elaborate on the implications of this study for theory and for the design of learning environments.

Implications for Theory. This study addresses a debate among researchers in the field of conceptual change. Specifically, one of the disagreements existing among researchers in the field of conceptual change is the extent to which pre-instruction conceptual knowledge is represented as a coherent structure versus a collection of elements that are activated differently based on context (see Özdemir & Clark, 2007 for discussion). Specifically, the study reported here engages with the debate between proponents of the dynamic view of ontology (e.g., Dreyfus et al., 2015b; Gupta et al., 2010; Scherr et al., 2012) and proponents of the Ontological Shift theory (e.g., Chi et al., 1994; Slotta et al., 1995) on the nature of novices and experts' ontological categorization. As discussed above, this study suggests that a coarse level of developing scientific expertise does involve starting to conceptualize some science concepts as a constrained-based process, and that novices are limited to a material substance ontology. Therefore, this study does provide some evidence in support of the Ontological Shift view proposed by Chi, Slotta and colleagues. However, as discussed above, a finer grain size of analysis of including close attention to gestures and the coordination between speech and gestures reveals ontological categorization is a more systemic construct that Chi and colleagues have not acknowledged: it is a system where various metaphors are enacted and coordinated leading to the construction of an ontological category. Viewed in this way, the evidence also provides some support for the position held by proponents of the dynamic view of ontology where novices and experts' ontological categorization involves the coordination of a variety of conceptual resources (including metaphors enacted by gestures). Such findings highlight complexities in novices and experts' thinking. Thus, this study has direct implications to theory in that it suggests an intermediate position that includes elements from the two competing theoretical perspectives. Conceptual change viewed from this intermediate perspective acknowledges a role for both what has been called "restructuring" (e.g., Chi et al., 1994) and "refinement" (e.g., Jeppsson et al., 2015).

Implications for Design of Learning Environments. The implications for theory just discussed above have implications for the design of instruction and suggests future research to evaluate the suggested design innovations. The theoretical position emerging from this study suggests instruction that builds on the proposed intermediate perspective in this study. That is, the proposed instructional design combines the approaches adopted by proponents of both the Ontological Shift theory and the dynamic view of ontology is likely to be particularly effective.

On the one hand, proponents of the Ontological Shift theory proposed that conceptual change entails radical restructuring. Based on that, the instructional approach adopted requires students to be made aware that they need to shift their conceptions from one ontological category to another. In more recent work, Chi et al. (2012) investigated the effectiveness of explicitly teaching students the constraint-based process ontological category through a computer simulation of diffusion, a particularly clear constraint-based process. Specifically, the dynamic computer simulations represent micro and macro levels of how two containers one filled with dye and the other with water diffuses as the valve is opened between the containers.

On the other hand, proponents of the dynamic view of ontology proposed that conceptual change requires refinement in the use of multiple resources; this view assumes continuity in learning where learners' initial conceptions are considered to be productive and that it is the aim of instruction to cultivate the effective activation of these resources (diSessa & Minstrell, 1998). Specifically, proponents of the dynamic view of ontology have highlighted the advantages of invoking multiple ontological metaphors that are context-sensitive (Scherr et al., 2012). For example, it has been suggested that it is valuable for learners to be provided with an effective learning environment (including visual representations and simulations) which strategically activate useful ontological conceptualizations, including the material substance ontology (Dreyfus et al., 2014; Scherr et al., 2012). On that basis, Scherr and colleagues developed the Energy Project: a professional development project conducted for science teachers (Close & Scherr, 2015; Daane et al., 2018; Scherr et al., 2012). This project advocates the strategic use of the substance metaphor of energy through the Energy Theater activity. The activity builds on a concrete learning environment where teacher/learners embody units of energy and use other representations (such as ropes) to demarcate components of a system to understand energy transfer and transformation in specific scenarios, such as cooling food in a refrigerator.

The intermediate perspective advocated in this thesis suggests that both types of recommendations are likely to be effective and would complement each other. That is, designing simulations to support the development of the constraint-based process ontological category would be expected to be helpful, this aligns with the instructional design proposed by Chi and colleagues. But in addition, features of these simulations and other instructional design features that activate strategically material substance conceptions and other available resources are also expected to contribute to effective learning, and this aligns with the instructional design proposed by proponents of the dynamic view of ontology. Some of the specific results of this study lead to particular recommendations. For instance, the analysis presented in this study helped in identifying resources that a learner could use to construct an understanding of heat transfer as a constraint-based process. Analysis of expert and novice explanations in heat problems provided evidence that the process of equilibration could be understood in terms of various spatial, material metaphors - e.g. the balance gestures produced by E1 and N4 discussed earlier. This balance gesture could be used as an inspiration for proposing an instructional approach to teach how kinetic energy of the molecules changes as two objects of different temperatures are brought into contact. That is, students may be provided with a dynamic simulation that promotes construing temperature change as an equilibration process. This simulation may be accompanied with a vertical scale showing the coordinated energy changes of both objects. This could be combined with other iconic representations showing the changing motion of molecules. As a result the simulation would be more likely to support construing the exchange of heat as a constrained-based process. This is one illustration of how the specific results of this study could provide ideas for instructional design. However, any such innovations would be need to be evaluated and so follow up research on the design of such simulations would be needed.

Limitations of the study

There are some limitations to this study that must be discussed. One of the limitations of this study lies in the presence of individual variations in the total gestural movements produced by participants. Such variation in gestural movements may have influenced the frequencies of gestural predicates and gestural types. This is because the identified gestural movements were later classified into different gestural types. Furthermore, gestural predications were defined as, metaphorical gestures referring to heat, light, or electric current concepts. Thus, such individual variations in gestural movements may have had an influence over study findings for the patterned production of gestural types and predicates. Following that, the findings reported here in this study are conclusive enough to provide a better understanding of the novices and experts' conceptualization of science concepts. Probably future research may replicate the current study while recruiting more participants to further explore patterns of production of gestural types and gestural predicates.

Another limitation of this study lies in the difficulties associated with identifying the meanings conveyed in gestures which influenced the analyses of gestural types and predications. Cienki (2010) has pointed out that the meanings conveyed by gestures can be underspecified since they depended on the speech modality. Cienki (2017) has gone to argue that researchers may misinterpret metaphorical gestures. Overall, given that the analysis of gesture is still a new area of research and methods of analysis are still being developed, there is a substantial degree of inference involved on the part of the researcher. More research is needed to investigate the effectiveness of the adopted procedure of gesture analyses in this study.

A third limitation of this study lies in focusing on the identification and analysis of gestural predicates. This has limited the analysis to focusing only on metaphorical gestures that only targets the science concepts heat, light and electric current. Hence, some of the gestures produced and their roles were not analyzed. Yet, including the analyses of different gestural types may have provided more knowledge about the types of the gestures produced and their roles in formulating science explanations across different levels of expertise. Probably, the current data emerging from this study may be used to explore the different types of gestures produced, how they were coordinated and their role in formulating abstract science explanations across different levels of expertise.

Finally, another limitation that may have influenced the study findings is differences in the educational system, culture, and language of participants recruited in this study compared to that of Slotta et al. (1995). Various studies conducted by Clark and colleagues (e.g., Clark, D'Anegelo, and Schleigh, 2011; Clark et al., 2013) and Tange, Yang and Levin (2020) have highlighted how differences in students' conceptions can arise due to contextual variables such as culture, school system and language. More specifically, this research has suggested that the extent to which learner conceptions are coherent (versus fragmented) may be due to these variables. Tange et al. (2020) have highlighted specifically how different languages contribute to students' conceptualizations in science. They have suggested that Chinese students formulated science explanations of the Earth unlike students in the USA and Greece. They trace this difference to the Chinese term for the Earth which explicitly refers to earth as a round-shaped ball. Similarly, Clark et al. (2011) have highlighted how students in Turkey, USA, Mexico, Philippines, and China formulated different science explanations of "force" based on the colloquial meaning of the word. The present study was conducted in English and the novices were students at a university in which English is the language of instruction and participants confirmed that English is the language in which they are most comfortable talking about science. However, English is not the students' native language, and this could have influenced the nature of their conceptions and their coherence. Therefore, it is possible that the differences between the results of this study and the study by Slotta et al. (1995) may be due to cross-linguistic differences of participants recruited in both studies. Future research could systematically examine such cross-linguistic differences in ontological predication.

Conclusion

This study aimed to address one of the arguments existing in the field of conceptual change on the extent to which students and experts' ontological categorization is dynamic as proposed by the dynamic view of ontology versus static as proposed by proponents of the Ontological Shift theory. The current study is, in part, a replication of the study conducted by

Slotta et al. (1995) while using gestures as a window onto ontological categorization in addition to the use of language. The results reported here provided an intermediate position that includes elements from the two competing theoretical perspectives. It is suggested that the shift towards greater expertise (i.e., conceptual change) entails refinement as well as radical restructuring where various metaphors are coordinated differently leading to the construction of a process ontological category. The activation and coordination of these metaphors are considered among the conceptual resources that support thinking about abstract science concepts.

REFERENCES

Abels, S. (2016). The role of gestures in a teacher-student discourse about atoms. *Chemistry Education Research and Practice, 17*(3), 618-628. doi: 10.1039/C6RP00026F

Alibali, M. W., & Goldin-Meadow, S. (1993). Gesture-speech mismatch and mechanisms of learning: What the hands reveal about a child's state of mind. *Cognitive Psychology*, *25*(4), 468-523.

Amin, T.G. (unpublished manuscript). Forms of Ontological Knowledge in Novices and Science Experts

Amin, T. G. (2009). Conceptual metaphor meets conceptual change. *Human Development*, *52*(3), 165-197.

Amin, T. G. (2015). Conceptual metaphor and the study of conceptual change: Research synthesis and future directions. *International Journal of Science Education*, *37*(5-6), 966-991.

Amin, T. G., Smith, C., & Wiser, M. (2014). Student conceptions and conceptual change: Three overlapping phases of research. In N. Lederman & S. Abell (Eds.), *Handbook of research in science education*, vol II (pp. 57–81). New York, NY: Taylor and Francis

Brown, D. & Hammer, D. (2008) Conceptual change in physics. In Vosniadou, S. (Ed.), *International Handbook of Research on Conceptual Change* (pp. 127-154). New York: Routledge.

Carey, S. (1986). Cognitive science and science education. *American Psychologist, 41*(10), 1123-1130. doi:10.1037/0003-066X.41.10.1123

Carey, S. (2009). *The origin of concepts*. US: Oxford University Press.

Chi, M. T. H. (2005). Commonsense conceptions of emergent process: Why some misconceptions are robust. *Journal of the Learning Sciences, 14*(2), 161-199. doi:10.1207/s15327809jls1402_1

Chi, M. T. H. (2013). Two kinds and four sub-types of misconceived knowledge, ways to change it, and the learning outcomes. In Vosniadou, S. (Ed.), *International Handbook of Research on Conceptual Change* (pp. 48-70). Abingdon: Routledge

Chi, M. T. H., & Slotta, J. D. (1993). The ontological coherence of intuitive physics. *Cognition and Instruction, 10*(2/3), 249-260. doi: 10.1080/07370008.1985.9649011

Chi, M. T. H., Slotta, J. D., & de Leeuw, N. (1994). From things to process: A theory of conceptual change for learning science concepts. *Learning and Instruction, 4*(1), 27-43. doi: 10.1016/0959-4752(94)90017-5

Chi, M. T. H., Roscoe, R. D., Slotta, J. D., Roy, M., & Chase, C. C. (2012). Misconceived causal explanations for emergent process. *Cognitive Science*, *36*(1), 1-61. doi:10.1111/j.1551-6709.2011.01207.x

Chue, S., Lee, Y. J., & Tan, K. C. D. (2015). Iconic gestures as undervalued representations during science teaching. *Cogent Education*, *2*(1), 1021554.

Church, R. B., & Goldin-Meadow, S. (1986). The mismatch between gesture and speech as an index of transitional knowledge. *Cognition*, *23*(1), 43-71.

Cienki, A. (2005). Image schemas and gesture. In Hampe, B. From perception to meaning: Image schemas in cognitive linguistics (pp. 421-442). Berlin/Boston: De Gruyter, Inc. doi:10.1604/9783110197532

Cienki, A. (2008). Why study metaphor and gestures? In Cienki, A., & Müller, C. (Eds.), *Metaphor and gesture* (pp. 6-24). Amsterdam: John Benjamins Publishing Company

Cienki, A. (2010). Multimodal metaphor analysis. In Cameron, L., & Maslen, R. *Metaphor analysis: Research practice in applied linguistics, social sciences and the humanities* (pp. 195-214). Bristol: Equinox Publishing Ltd.

Cienki, A. (2016). Analyzing metaphor in gestures: A set of metaphor guidelines for gesture (MIDG-G). In Semino, E., & Demjén, Z. (Eds.), *The Routledge Handbook of Metaphor and Language* (pp. 131-147). Abingdon, Oxon: Routledge.

Cienki, A., & Müller, C. (2008). *Metaphor and gesture*. Amsterdam: John Benjamins Publishing Company.

Close, H. G., & Scherr, R. E. (2012). Differentiation of energy concepts through speech and gesture in interaction. In *AIP Conference Proceedings* (Vol. 1413, No. 1, pp. 151-154). AIP.

Close, H. G., & Scherr, R. E. (2015). Enacting conceptual metaphor through blending: Learning activities embodying the substance metaphor for energy. *International Journal of Science Education, 37*(5-6), 839-866. doi:10.1080/09500693.2015.1025307

Congdon, E. L., Novack, M. A., & Goldin-Meadow, S. (2018). Gesture in experimental studies: How videotape technology can advance psychological theory. *Organizational Research Methods, 21*(2), 489-499. doi:10.1177/1094428116654548

Crowder, E. M. (1996a). Gestures at work in sense-making science talk. *The Journal of the Learning Sciences*, *5*(3), 173-208.

Crowder, E. M. (1996b). *Gesture and perspective-taking in science talk: When learning histories vary*.

Daane, A. R., Haglund, J., Robertson, A. D., Close, H. G., & Scherr, R. E. (2018). The pedagogical value of conceptual metaphor for secondary science teachers. *Science Education*, *102*(5), 1051-1076. doi:10.1002/sce.21451

diSessa, A. A. (1988). Knowledge in pieces (pp. 57-78) Psychology Press. doi:10.4324/9780203771242-10

diSessa, A. A. (1993). Toward an epistemology of physics. *Cognition and instruction*, *10*(2-3), 105-225.

diSessa, A. A. (2017). Conceptual change in a microcosm: Comparative learning analysis of a learning event. *Human Development, 60*(1), 601.

diSessa, A. A., & Minstrell, J. (1998). Cultivating conceptual change with benchmark lessons. In Greeno J. (Eds.), *Thinking practices in mathematics and science learning* (pp. 165-198) Routledge. doi:10.4324/9780203053119-14

Duit, R. (1987). Should energy be illustrated as something quasi-material? *International Journal of Science Education*, *9*(2), 139-145.

Dreyfus, B. W., Geller, B. D., Gouvea, J., Sawtelle, V., Turpen, C., & Redish, E. F. (2014). Ontological metaphors for negative energy in an interdisciplinary context. *Physical Review Special Topics-Physics Education Research, 10*(2), 020108. doi:10.1103/PhysRevSTPER.10.020108

Dreyfus, B. W., Gupta, A., & Redish, E. F. (2015a). Applying conceptual blending to model coordinated use of multiple ontological metaphors. *International Journal of Science Education*, *37*(5-6), 812-838. doi:10.1080/09500693.2015.1025306

Dreyfus, B. W., Sohr, E. R., Gupta, A., & Elby, A. (2015b). " Classical-ish": Negotiating the boundary between classical and quantum particles.

Feynman, R.P., Leighton, R.B., & Sands, M. (1963).*The Feynman lectures on physics*. Vol. 1–3. Reading:Addison-Wesley.

Givry, D., & Roth, W. M. (2006). Toward a new conception of conceptions: Interplay of talk, gestures, and structures in the setting. *Journal of Research in Science Teaching*, *43*(10), 1086-1109

Goldin-Meadow, S. (2003). *Hearing gesture: How our hands help us think*. Cambridge, Mass: Harvard University Press.

Gupta, A., Hammer, D., & Redish, E. F. (2010). The case for dynamic models of learners' ontologies in physics. *Journal of the Learning Sciences, 19*(3), 285-321. doi: 10.1080/10508406.2010.491751

Hammer, D., Gupta, A., & Redish, E. F. (2011). On static and dynamic intuitive ontologies. *Journal of the Learning Sciences, 20*(1), 163-168. doi: 10.1080/10508406.2011.537977

Henderson, J. B., Langbeheim, E., & Chi, M. T. (2018). Addressing robust misconceptions through the ontological distinction between sequential and emergent process. In Amin, T., & Levrini, O. (Eds.), *Converging Perspectives on Conceptual Change: Mapping an Emerging Paradigm in the Learning Sciences*. (pp. 26-33). Milton: Routledge Ltd. doi:10.4324/9781315467139

Jeppsson, F., Haglund, J., Amin, T. G., & Strömdahl, H. (2013). Exploring the use of conceptual metaphors in solving problems on entropy. *Journal of the Learning Sciences*, *22*(1), 70-120.

Jeppsson, F., Haglund, J., Amin, T. G., Lärande, E., Naturvetenskap, (2015). Varying use of conceptual metaphors across levels of expertise in thermodynamics. *International Journal of Science Education, 37*(5-6), 780-805. doi:10.1080/09500693.2015.1025247

Keil, F. C. (1979). *Semantic and conceptual development: An ontological perspective*. Cambridge, Mass: Harvard University Press.

Kendon, A. (2005). *Gesture: Visible action as utterance*. Cambridge: Cambridge University Press.

Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago, ILL: University of Chicago Press.

McCloskey, M. & Kargon, R. (1988). The meaning and use of historical models in the study of intuitive physics. In S. Strauss (ed.), *Ontogeny, phylogeny, and historical development, Human Development*, vol. 2. Norwood, NJ: Ablex Publishing Corporation.

McNeill, D. (1985). So you think gestures are nonverbal? *Psychological Review, 92*(3), 350-371. doi: 10.1037/0033-295X.92.3.350

McNeill, D. (1992). *Hand and mind: What gestures reveal about thought*. University of Chicago press.

McNeill, D. (2005). *Gesture and thought*. Chicago: University Of Chicago Press.

McNeill, D., & Duncan, S. D. (2000). Growth points in thinking-for-speaking. (pp. 141-161) Cambridge University Press. doi:10.1017/CBO9780511620850.010

Nersessian, N. J. (1989). Conceptual change in science and in science education. *Synthese, 80*(1), 163-183. doi:10.1007/BF00869953

Novack, M. A., & Goldin-Meadow, S. (2017). Gesture as representational action: A paper about function. *Psychonomic Bulletin & Review, 24*(3), 652-665. doi:10.3758/s13423-016-1145-z

Núñez, R. (2015). Some Challenges in the Empirical Investigation of Conceptual Mappings and Embodied Cognition in Science Education: Commentary on Dreyfus, Gupta and Redish; and Close and Scherr. *International Journal of Science Education*, *37*(5-6), 867-875.

Reiner, M., Slotta, J. D., Chi, M. T. H., & Resnick, L. B. (2000). Naive physics reasoning: A commitment to substance-based conceptions. *Cognition and Instruction, 18*(1), 1-34. doi:10.1207/S1532690XCI1801_01

Roth, W. M. (1999). The evolution of umwelt and communication. *Cybernetics & Human Knowing*, 6(4), 5-23

Roth, W. M. (2000). From gesture to scientific language. *Journal of pragmatics*, *32*(11), 1683-1714.

Roth, W. (2001). Gestures: Their role in teaching and learning. *Review of Educational Research, 71*(3), 365-392. doi: 10.3102/00346543071003365

Roth, W., & Lawless, D. (2002a). Scientific investigations, metaphorical gestures, and the emergence of abstract scientific concepts. *Learning and Instruction, 12*(3), 285-304. doi: 10.1016/S0959-4752(01)00023-8

Roth, W., & Lawless, D. (2002b). Signs, deixis, and the emergence of scientific explanation. *Semiotica, 138*(1-4), 95-130. doi:10.1515/semi.2002.016

Roth, W., & Lawless, D. (2002c). When up is down and down is up: Body orientation, proximity, and gestures as resources. *Language in Society, 31*(1), 1-28. doi:10.1017/S0047404501010016

Roth, W., & Welzel, M. (2001). From activity to gestures and scientific language. *Journal of Research in Science Teaching, 38*(1), 103-136. doi:10.1002/1098-2736(200101)38:1<103:AID-TEA6>3.0.CO;2-G

Scherr, R. E. (2008). Gesture analysis for physics education researchers. *Physical Review Special Topics-Physics Education Research*, 4(1), 010101.

Scherr, R. E., Close, H. G., McKagan, S. B., & Vokos, S. (2012). Representing energy. I. Representing a substance ontology for energy. *Physical Review Special Topics-Physics Education Research*, 8(2), 020114.

Scherr, R. E., Close, H. G., Close, E. W., Flood, V. J., McKagan, S. B., Robertson, A. D., Vokos, S. (2013). Negotiating energy dynamics through embodied action in a materially structured environment. *Physical Review Special Topics - Physics Education Research, 9*(2), 020105. doi:10.1103/PhysRevSTPER.9.020105

Siegler, R. S. (1998). *Emerging minds: The process of change in children's thinking* (New ed.). New York: Oxford University Press.

Slotta, J. D. (2011). In defense of chi's ontological incompatibility hypothesis. *Journal of the Learning Sciences, 20*(1), 151-162. doi:10.1080/10508406.2011.535691

Slotta, J. D., & Chi, M. T. H. (2006). Helping students understand challenging topics in science through ontology training. *Cognition and Instruction, 24*(2), 261-289. doi:10.1207/s1532690xci2402_3

Slotta, J. D., Chi M. T. H., & Joram, E. (1995). Assessing students' misclassifications of physics concepts: An ontological basis for conceptual change. *Cognition and Instruction, 13*(3), 373-400. doi: 10.1207/s1532690xci1303_2

Vosniadou, S. (2013). *International handbook of research on conceptual change* (Second ed.). New York: Routledge. doi:10.4324/9780203154472

Vosniadou, S., & Skopeliti, I. (2017). Is it the earth that turns or the sun that goes behind the mountains? students' misconceptions about the day/night cycle after reading a science text. *International Journal of Science Education, 39*(15), 2027-2051. doi:10.1080/09500693.2017.1361557

Wiser, M. (1997). Use of history of science to understand and remedy students' misconceptions about heat and temperature. In Schwartz, J. L. *Software Goes to School: Teaching for Understanding with New Technology* (pp. 23-38). New York: Oxford University Press. doi:10.1093/acprof:oso/9780195115772.003.0002

Wiser, M., & Smith, C. (2016). How is conceptual change possible? Insights from science education. In Wiser, M., *Core knowledge and conceptual change* (pp. 29-52). New York: Oxford University Press. doi:10.1093/acprof:oso/9780190467630.003.0003

APPENDIX A

PREDICATE CODING SCHEME

Predicate coding scheme used by Slotta et al. (1995) in analyzing novices and experts' verbal explanations of matter and process categorization with some examples.

Matter Predicates	*Process Predicates*
Block: keep, bounce, hits, stops	Transfer: Energy propagates through, transfer from one to another.
Contain: holds in, stores, keeps in, get out, into	Excitation: energy excited, a lot of phonon nodes to excite, need a lot of energy to excite them.
Moves: goes, leaves, flows, comes Rest: stops, stays, sits	Interaction: the light energy is absorbed and transformed, the interaction of the electric and magnetic fields
Supply: provides, comes from, gives off, comes out	Equilibrium seeking: The system finds its way into equilibrium
Quantified: some, all, most, less, none of, lots, little bit, as much	System wide: These are all in parallel, there's an electric field throughout the wire, there's a field present throughout the wire, all see the same potential.
Comes to rest: stops, stays	Light as combined wave: They all see (the potential) at the exact same time
Absorbed: takes in, soaks, absorb	
Can be consumed: burned up, used up Absorb: soaks, takes in	Simultaneously: It would have red (spectral) lines and green lines in it.
Accumulate: fills up, builds up, add on, keeps building	Movement: charged particle moving in an electric field," "the light is a traveling electromagnetic wave.
ColorAdd: adds like colored paints, red and blue make purple, just like with paints Equivalent amount: divides up equally, same amount	

APPENDIX B

PROBLEMS PROVIDED FOR PARTICIPANTS

The following is the set of problems that will be provided for participants which is part of an ongoing research. They have the same form as those provided by Slotta et al. (1995).

Heat

Physics Concept Problem

1A. Two cups of hot coffee are poured, one into a styrofoam cup and one into a ceramic mug, and both cups are sealed with airtight lids. What will we find after leaving the two cups sit on a tabletop for twenty minutes?

a. The coffee in the ceramic mug is hotter than that in the styrofoam cup.

b. The coffee in the styrofoam cup is hotter than that in the ceramic mug.

c. Neither cup has hotter coffee than the other.

d. Other

Material Substance Isomorph

1B. Two different balloons are filled with Helium gas, one made of an ordinary paper bag and one made of durable elastic rubber, and both are sealed tightly at the opening. What will we find after leaving the two balloons floating inside a closet for several hours?

a. The balloon made of rubber is more buoyant than the one made of paper.

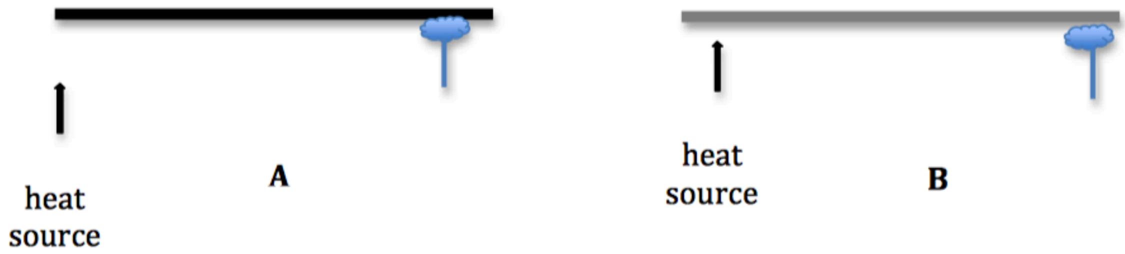
b. The balloon made of paper is more buoyant than the one made of rubber.

c. Neither balloon is more buoyant than the other.

d. Other

Physics Concept Problem

2A. Two metals rods, A and B, are identical in size, but made of different metals where A is more dense than B. A blob of wax is attached to the end of each rod and a pin is stuck in the wax. At the other end both rods are heated by the same source of heat for the same time.



Which of the following is correct?

a. The wax melts and the pin falls to the ground in the case of rod A before rod B.

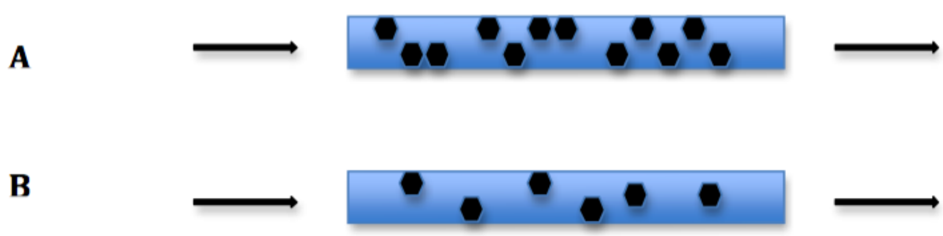
b. The wax melts and the pin falls to the ground in the case of rod B before rod A.

c. The blobs of wax melt and the pins fall in both rods at the same time.

d. Other

Material Substance Isomorph:

2B. Two tubes, A and B, are identical in size. Both contain small stones; rod A has more stones than rod B. Water is pumped through both tubes.



If water is pumped from identical sources into each tube which of the following is correct?

a. Water emerges from tube A before tube B.

b. Water emerges from tube B before tube A.

c. Water emerges from both tubes at the same time.

d. Other

Physics Concept Problem

3A. Two identical iron cubes, A and B, are placed in contact with one another. Cube A is hotter, with a temperature of 80 degrees Celsius, while cube B is at 50 degrees Celsius. After some time both cubes reach a temperature of 65 degrees Celsius. Which of the following is correct?

a. Using a very sensitive electronic balance, it is possible to discover that cube A has become lighter than it was before it was put into contact with cube B.

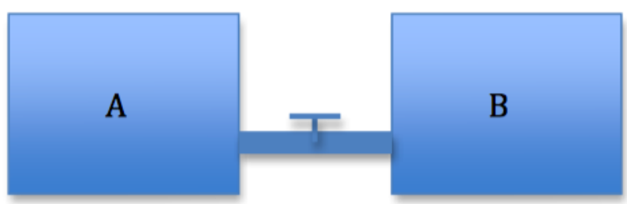
b. Using a very sensitive electronic balance, it is possible to discover that cube B has become lighter than it was before it was put into contact with cube A.

c. Using a very sensitive electronic balance, it is possible to discover that the two cubes are both the same weight as they were before they were put into contact.

d. Other

Material Substance Isomorph:

3B. Two identical containers have two different amounts of oxygen gas: container A has 0.8 moles of oxygen gas while container B has 0.5 moles When the two containers are connected as show below, we end up with 0.65 moles in each container.



Which of the following is correct when the connection between the two containers is then removed?

a. Using a very sensitive electronic balance, it is possible to discover that container A has become lighter than it was before it was connected to container B.

b. Using a very sensitive electronic balance, it is possible to discover that container B has become lighter than it was before it was connected to container A.

c. Using a very sensitive electronic balance, it is possible to discover that the two containers are both the same weight as they were before they were put into contact.

d. Other

Light

Physics Concept Problem

4A. The same light bulb is turned on during the daytime and late at night when it is dark. Which of the following is correct?

a. Light from the bulb can be detected further from the source at night than during the daytime.

b. Light from the bulb can be detected further from the source during the daytime than at night.

c. Light can be detected at the same distance from the source during the day as at night.

d. Other

Material substance isomorph

4B. Two identical hockey pucks A and B are pushed with the same force along two different ice tracks. Puck A is pushed along a track where that ice has been recently polished. Puck B is pushed along a track that has been used a lot and has not been polished recently since this heavy use. Which of the following is correct?

a. Puck B will stop further along the track than puck A.

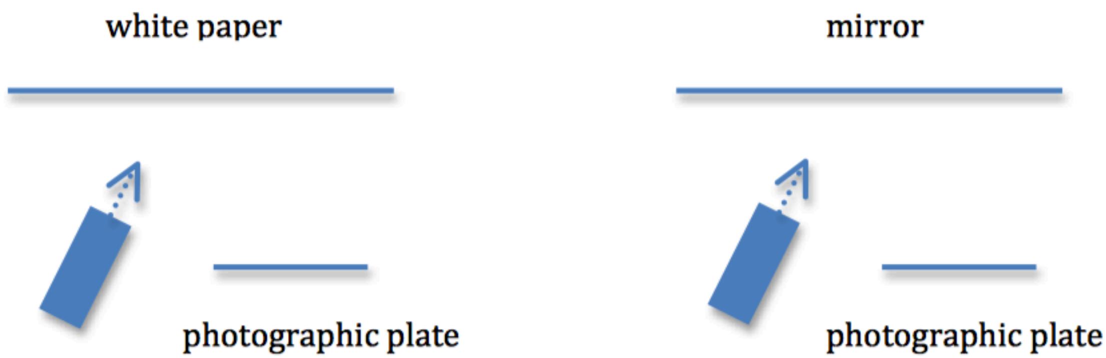
b. Puck A will stop further along the track than puck B.

c. Both pucks will stop at the same distance.

d. Other

Physics Concept Problem

5A. A beam of white light is directed at an angle towards either a piece of white paper or a mirror (as shown in situations A and B below). In each situation, a photographic plate is placed in the position shown to see if light can be detected at the location of the plate.



Which of the following is correct?

a. The photographic plate will detect light in situation A but not B.

b. The photographic plate will detect light in situation B but not A.

c. The photographic plate will detect light in both situations.

d. Other

Material Substance Isomorph

5B. A ball is kicked towards a wall in two different situations. In situation A the wall is a hard brick wall. In situation B the wall is padded with a firm cushion like material. A bucket is placed on its side at a position to allow it to catch the ball after it hits the wall. Which of the following is correct?

a. The ball will end up in the bucket in situation A but not B.

b. The ball will end up in the bucket in situation B but not A.

c. The ball will end up in the bucket in both situations.

d. Other

Physics Concept Problem

6A. A beam of red light is passed through a blue filter. The beam emerging from the filter is projected onto a white screen. Which of the following is a correct statement about the color of the patch of light appearing on the screen?

a. The light patch will be black.

b. The light patch will be purple.

c. The light patch will be neither black nor purple.

d. Other

Material Substance Isomorph

6B. The same amount of red paint and blue paint are mixed together. The resulting mixture is mixed thoroughly until a uniform new color is produced. What is the color of the resulting mixture?

a. Purple

b. Black

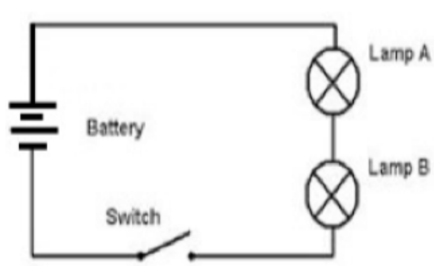
c. Neither purple nor black

d. Other

Electric Current

Physics Concept Problem

8A. The circuit below depicts a battery connected to two identical light bulbs. When the switch is closed it completes the circuit.



Which of the following is a correct statement about what will happen when the switch is closed?

a. Bulb A lights up more brightly than bulb B.

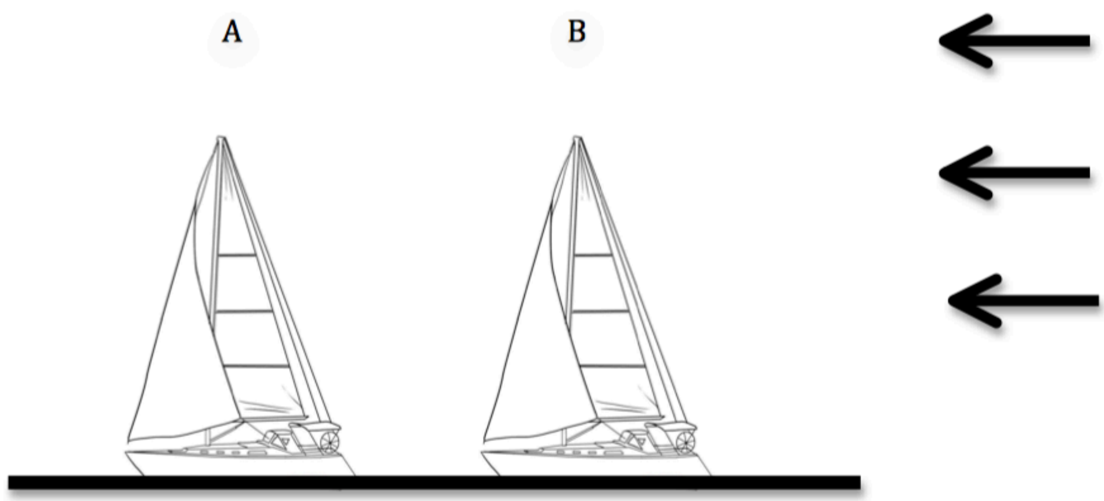
b. Bulb B lights up more brightly than bulb A

c. Both bulbs light up to the same degree

d. Other

Material Substance isomorph:

8B. Two sailboats are participating in a race as depicted in the picture below. Boat B is behind boat A and the wind is currently blowing in the direction of the arrows.



Which of the following predicts best what is likely to happen next?

a. Boat A will accelerate more and therefore make progress in catching up to boat

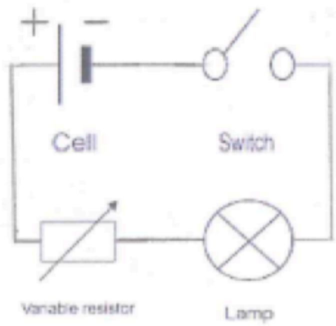
b. Boat B will accelerate more and therefore increase its lead over boat A.

c. Both boats will continue moving at the same speed as before.

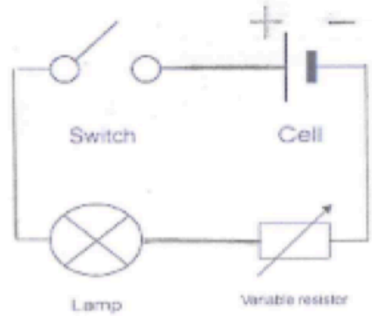
d. Other

Physics Concept Problem

8A. Two circuits A and B are drawn below. They are identical in all respects except for the position of the resistor. Both resistors can be adjusted so that they can provide variable resistance. In A, the resistor is between the +ve terminal of the battery and the bulb. In B, the resistor is between the -ve terminal and the bulb.



Circuit A



Circuit B

Which of the following predictions is correct?

a. In one of the two circuits, decreasing the resistance will increase the brightness of the bulb but in the other circuit decreasing the resistance will have no effect on the brightness of the bulb.

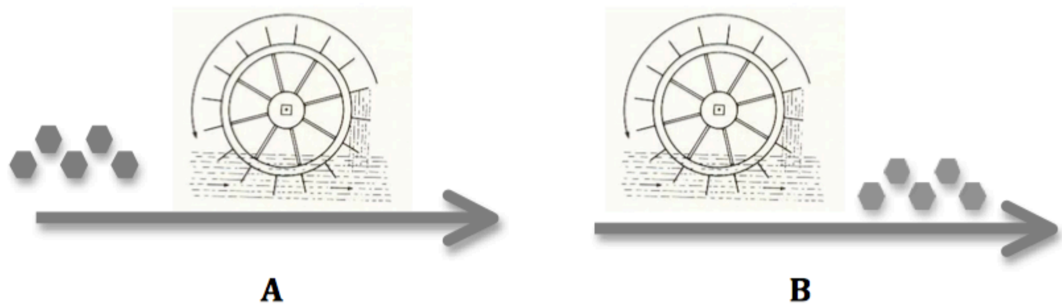
b. Varying resistance of either resistor will not have an effect on the bulb.

c. Varying either resistance in the same way will have the same effect on the bulb.

d. Other

<u>Material Substance Isomorph</u>

8B. The two pictures below depict an identical water wheel that is rotated by the flow of a small river. The arrow indicates the direction of flow of the river. In picture A, the water wheel is placed just after some large rocks in the river. In picture B, the water wheel is placed just before the rocks.



Which of the following predictions is correct?

a. Removing some of the rocks in A will speed up the water wheel but removing some rocks of the rocks in B will not have an effect on the water wheel.

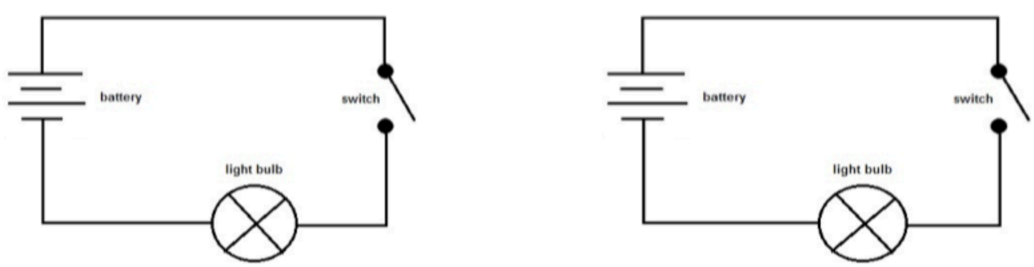
b. Removing some of the rocks in the river will not have an effect on the water wheel in either case.

c. Removing the same amount of rocks in each case will have the same effect on the water wheel.

d. Other

Physics Concept Problem

9A. The two circuits below are identical except for the battery. In circuit A, it is a 1.5 Volt battery. In circuit B, it is a 1.0 Volt battery.



A (1.5 V battery) **B** (1.0 V battery)

Which of the following predictions is correct?

a. The battery in B will turn off first before the battery in A.

b. Both batteries will turn off at the same time.

c. There isn't enough information to determine which battery will turn off first.

d. Other

Material Substance Isomorph

9B. Two otherwise identical cars have been fitted with different sized gas tanks. The tank in car A is 1.5 times the size of the tank in car B. Which of the following predictions is correct if both cars are traveling at the same speed having begun with a full tank of gas?

a. The tank in car B runs out of gas before car A.

b. The tanks in both cars will run out of gas at the same time.

c. There isn't enough information to determine which car will run out of gas first.

d. Other

APPENDIX C

PARTICIPANTS' PROFILE

This appendix presents the profiles of participants. Participants were recruited from a private university that has English as its language of instruction. As such, all the professors and students expressed their comfort in talking in English. Specifically, all professors had written their PhD dissertations in English.

- E1: This expert participant is a professor in Chemical Engineering. He had studied science in Arabic until age 14 then shifted to English. Specifically, the professor teaches introductory courses in chemical engineering and thermodynamics. The dissertation topic was on heat exchange and transfer
- E2: This expert participant was a professor in Physics. He teaches courses in plasma physics for undergraduate students and introductory courses for life science. He also teaches electricity courses for engineering. His dissertation was mostly experimental physics.
- E3: This expert is a professor in Chemistry. His dissertation was on spectroscopy and teaches General Chemistry and Physical Chemistry courses for undergraduate and graduate students.
- E4: The expert is a professor in Geology who teaches courses in Physical Geology, Field Methods, and Geological Mapping. Her PhD dissertation was about hydrogeology.
- N1: This novice participant was a senior student who is majoring in English Literature. The participant had attending the Lebanese educational system in high school and the only science-related courses she had taken were general education and livestock production elective courses.

- N2: This novice participant is a senior student double Majoring in Media and Communication and Political science. This participant had not taken any prior science courses and had attended schooling in an American system.
- N3: The participant is a senior student majoring in Computer Science. The participant had attended Lebanese educational system. The previous natural science courses taken were introductory biology course and water and environment.
- N4: The participant is a junior student majoring in Graphic Design. She had attended a Lebanese educational system in high school and had taken introductory natural science course and introductory physics course.

APPENDIX D

EXAMPLES OF VERBAL PREDICATES

This appendix illustrates how verbal data was coded for predicate use. The examples provided here include detailed instances where experts used matter and/or process predications and where novices used matter predications. The following two tables are examples of Matter and Process predications.

Matter Predications: The matter predications were used by novices and experts.

Physics Concept Problem	*Verbal Speech*	*Verbal Predication*
Heat	N2: So, in [metal rod] B I am guessing *if you put heat onto it [metal rod]*, I feel it will all fall.	Supply, Matter: heat is conceptualized as a substance that is added.
	E3: It is like it is an insulator it will not allow the heat to pass easily like the ceramic mug.	Move, Matter: heat is conceptualized as a substance that moves through the cup.
	N3: "Because at A it's [metal rod] more dense so it needs more time to… the heat to reach the end of the rod".	Move, Matter: Heat is thought of as a moving substance
Light	E3: If we *pass a bright light* then the blue filter *will pass only* the blue light.	Move, Matter: light is conceptualized as a substance that moves and passed through the filter paper
	E1: You are putting light through a filter	Contain, Matter: light is conceptualized as a substance that is contained: it can be put and removed.

	N1: But in the case of paper I think it [light] would go through it and not reflect.	Move, Matter: Light is conceptualized as a substance that moves through paper.
Electricity	E1: Again V=IR., depend where it [current] is heading, where is the positive and where is the negative.	Move, Matter: electric current/electricity is thought of as a moving substance.
	E4: I'm just thinking that if I decrease the resistance, then I'll allow more, more, like more intensity.	Block, Matter: Electric current/electricity is conceptualized as a substance that is blocked by resistance. Once resistance is removed more current is allowed to move.
	N3: The light bulb is consuming what's in the battery so the one with the 1., 1 volt will be empty before the 1.5.	Supply, Matter: electric current is conceptualized as a substance that is supplied by the battery

Process Predications: The process predications were produced only by experts

Physics Concept Problem	*Verbal Speech*	*Verbal Predication*
Heat	E4: So this *metallic bond (3ande) we have the orbits with electrons* and I assume that electrons are equal to protons so, so a metal that is denser is actually, *has more electrons so it is more conductive*	SystemWide, Process: heat conduction is construed as constrained by a system (i.e. atomic model). If electrons are equal to protons, then the metal will conduct heat more.
	E1: The form of heat is through the equation Newtons equation in terms of the conduction of heat.	SystemWide, Process: heat is conceptualized to be constrained by Newton's law.
	E4: And then if its more conductive then the wax will melt first because the *heat will propagate*, so going into molecular.	Transfer, Process: heat/thermal conductivity is construed as a process occurring due to the transfer of heat in metal.
Light	E2: Your detector detects the ambiance light plus your bulb light.	SystemWide, Process: light detection is conceptualized as a process governed by a mathematical formula
	E1: I think they [referring to surfaces] will both detect [light] but at various levels.	Interaction, Process: light is conceptualized as a process occurring upon its interaction with surfaces.
	E2: It really depends on the light that *is made up of waves.*	Combined Wave: Light is conceptualized as composed of waves

Electricity	E2: The current is equal to potential difference, multiplies divided by R: R is the same, but the V is higher, so the current is higher.	SystemWide, Process: electric current is conceptualized as a process constrained by Ohm's law.
	E1: But it is the rate that got the actual energy is being transferred, so it's the power.	Transfer, Process: electric current is conceptualized as a process occurring through transfer.

One of the challenges faced lies in identifying determining whether a particular code is either matter or process. Consequently, we were conservative when analyzing data such that these instances were settled by discussion with another researcher, and we opted to choose the position that does not favor the theoretical position of the researchers. For example, E4 stated "Maybe it may mix a little bit in terms of atoms or electrons or vibration". This was considered as excitation process. It can be noted though that the use of matter predications (mix a little bit in terms of atoms) reveal materialistic conceptualization. Another example was evident in E1 as he articulated: "One is hotter so the heat will go from the higher to the lower until they reach equilibrium and they will have same temperature.". This sentence was considered as a process predicate and not matter. Knowing that the participant used materialistic terminologies (heat will go) yet the overall phrasing of heat reveal it is being construed as a process.

Another challenge faced was ensuring that the targeted science concepts (heat, light, and electricity/electric current) are the ones that are being predicated and not another concept. For example, saying "they [coffee] would have cooled down but they would not have basically cooled down to the same level" is not predicating the heat concept. Rather, the phrase is conceptualizing *coolness/hotness* to be a quantity. Then, this phrase reveals predicating coolness and not heat.

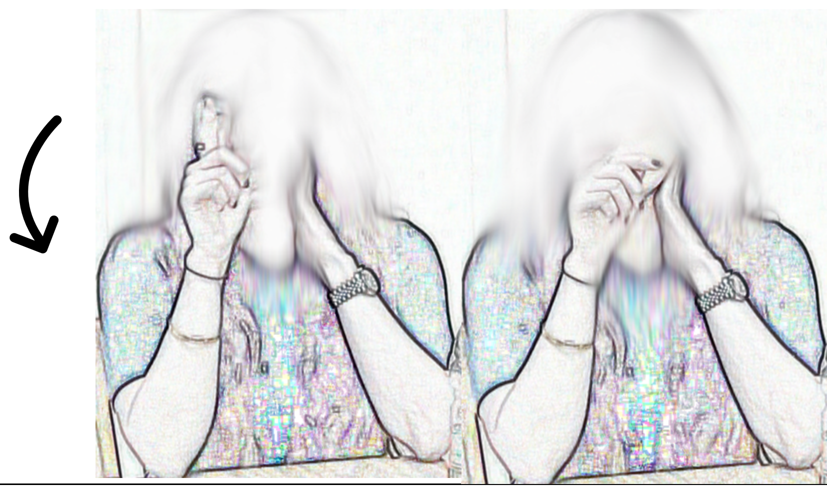
APPENDIX E
GESTRUAL CLASSIFICATION

This appendix provides examples on how gestural movements were classified. It shall be noted that distinguishing between iconic and metaphoric gestures was not clear given the context of speech. These gestural movements were considered as iconic/metaphoric and were not used in the analysis of gestural predications. This appendix will include examples of such gestures as well.

<table>
<tr><td colspan="2">Examples of Concrete Referential Gestures</td></tr>
<tr><td colspan="2">Iconic, referential gesture</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Speech</td><td>I'm just trying to link this to if I would like <u>heat a pot on the stove.</u></td></tr>
<tr><td>Gesture</td><td>Both hands have a grasp shape with the palms facing each other while articulating heat pot on a stove. Thus, the hand is representing shape of a pot</td></tr>
<tr><td colspan="2">Deictic</td></tr>
</table>

Speech	*I mean neither of the cubes are at melting points*
Gesture	The palm of the left hand is facing the ceiling. Hand is pointing to the middle of the screen. Thus, Hand is referring to the problem as presented on a projector.

<table>
<tr><td colspan="2">Examples of Abstract Referential Gestures</td></tr>
<tr><td colspan="2">Metaphoric</td></tr>
<tr><td colspan="2"></td></tr>
<tr><td>Speech</td><td>Whereas in [metal rod] B its much weaker for it to sustain the heat being applied to it.</td></tr>
<tr><td>Gesture</td><td>The physical referent is embodying a forward jumping movement two times. The contextual topic is less dense metals doesn’t allow heat to stay/remain (i.e., sustained) in the metal rod. Thus, heat is metaphorically construed as a substance that is supplied by a source and has a path in which the denser the metal the more heat is sustained in it.</td></tr>
<tr><td colspan="2">Deictic, metaphoric</td></tr>
<tr><td colspan="2"></td></tr>
</table>

Speech	*Because the whole circuit should be complete: the positive pole the negative pole.*
Gesture	Both hands have a grasp shape with the palms located towards up. RH is located at a higher level than LH. The physical referent is holding two objects in the hand. Contextual topic is poles if electric circuit. Thus, the hands reveal metaphorically construing the poles to be located in the hand.
Examples of Iconic/Metaphoric Gestures	
	
Speech	*I will go with C because it is the same circuit.*
Gesture	The physical referent an object moving on a circular path. The contextual referent is the electric current (i.e., energy) being the same. Thus, the hand movement reveals metaphorically construing electric current as an object that moves from battery (i.e., positive terminal) to bulb A. Or the hand circular movement is refereeing to the circuit diagram present on the screen.

<table>
<tr><td colspan="2"></td></tr>
<tr><td>Speech</td><td>Like if the switch is on, if its off it will not work, if it’s on it will work.</td></tr>
<tr><td>Gesture</td><td>The physical referent is something that is moving in a horizontal motion. The contextual topic is electricity passing through wire when current is on. Thus, electricity is metaphorically construed as a moving substance. Or the hand circular movement is refereeing to the circuit diagram present on the screen</td></tr>
</table>

APPENDIX F

LIST OF IMAGE SCHEMAS

This appendix provides a brief description of the image schemas discussed by Johnson (1987) in his book *The Body in the Mind: The bodily basis of meaning, imagination, and reason* supported by examples on how they represent bodily experiences.

Name	*Description of Image Schema*	*Examples of Experiential Basis*
Path	Source, trajectory, and end point	Throwing a ball, walking from one place to another
Container	An object that is either *in* or *out* the container; physical objects have boundaries .	Moving from room to another moving *out* of the room; houses are also containers
Balance	Starts with our experiences with acts of balancing (i.e., learning how to balance forces)	Riding a bike, walking, twin-pan balance, balances views/emotions, balancing equations…etc.
Scale	Based on qualitative and quantitative (i.e., amount) experiences.	Pouring water in a cup and having the water level rise up; piling up books
Cycle	Begins with a starting point, moves into a sequence of points, and returns to its initial point to start another cycle.	Heartbeat, breathing, season change

APPENDIX G

ILLUSTRATIONS OF EXAMPLES OF GESTURAL PREDICATES

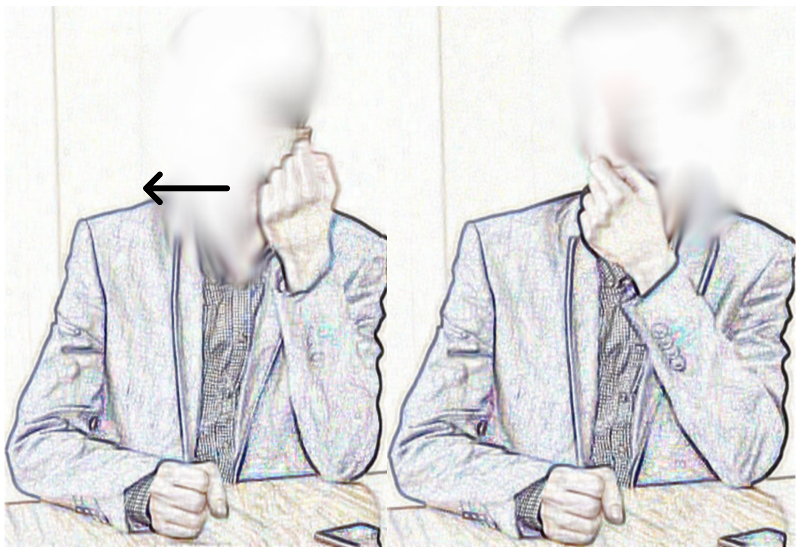
This appendix presents examples on how gestural predicates were identified and analyzed based on novices and experts' protocols. It shall be noted given the evidence emerging from this study, a new matter predication was added to the coding scheme developed by Slotta et al. (1995) which is Object, matter predication. This predication embodies a particular science concept (heat, light, or electricity) as an object that is being held in the hand. The following sections will provide illustrations of gestural predicates produced.

<table>
<tr><td colspan="3">Illustrations of Gestural Predications of Heat</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Speech</td><td colspan="2">You will have no idea what is the thermal conductivity of the metals for it to be able to conduct the heat and therefore to be able to get the wax to actually melt.</td></tr>
<tr><td>Gesture</td><td>The physical referent is an object moving from left to right horizontally. The contextual topic is conduction of heat in dense metals. Thus, heat is construed as something that moves along the rod starting from the rod till reaching the wax.</td><td>Move, Matter</td></tr>
</table>

		
Speech	*Whereas in [metal rod] B its much <u>weaker for it to sustain the heat</u> being applied to it.*	
Gesture	The physical referent is embodying a forward jumping movement two times. The contextual topic is less dense metals doesn’t allow heat to stay/remain (i.e., sustained) in the metal rod. Thus, heat is metaphorically construed as a substance that is supplied by a source and has a path in which the denser the metal the more heat is sustained in it.	Supply, Matter
		

Speech	*So there is no exchange of mass. The only thing exchanged is energy between body A and B.*	
Gesture	The physical referent is the opposite up and down movement of two objects that are being balanced. The contextual topic is the exchange of energy between A and B upon being in contact. Thus, the hand movement embodies the metaphor Equilibrium As Balance where thermal equilibrium is construed as physical balance between two objects being located at the same level of axis. Also, it is construed as a quantity located on a vertical scale and Change in Quantity is Change in Location In Space: More Energy Is Up And Less Energy Is Down. This is evident in the coordination of the up and down movement of both hands: what an object loses energy the other gains.	Equilibration, Process

Illustrations of Gestural Predications of Light	
	
Speech	*Your detector detects the ambiance light plus your bulb light*

Gesture	The physical referent is holding something in the hands. The contextual topic is light being detected by detector. Thus, light is metaphorically construed as something that is held by the hands.	Object, Matter
		
Speech	*When it (light) passes through the filter the colors will be mixed*	
Gesture	The physical referent is something moving in a horizontal movement. The contextual topic is light being filtered. Thus, light is metaphorically construed as a substance that moves.	Move, Matter

Illustrations of Gestural Predications of Electricity		
 		
Speech	*It [electric current] either makes it produces light or not.*	
Gesture	(a) The physical referent is an object moving horizontally. The contextual topic is light production. Thus, the electricity is metaphorically construed as a moving substance.	Move, Matter
	(b) The physical referent is something moving in cyclic PATH repetitively. The contextual topic is light being produced by the bulb. Thus, the cyclic movement reveal construing electricity as a	Supply, Matter

	substance that has a source and end point: the sequence starts by initial state of lightening a bulb then into turning off state. Also, the repetitive motion of the hand reveals MORE IN FORM IS MORE IN CONTENT: The more electricity the more light will be produced.	

One of the challenges faced in the analysis of gestural predicates was in identifying what concept was actually being predicated. These instances were resolved by discussion with another researcher as mentioned in the methodology chapter. The following is an example that reveals that temperature/coolness -and not heat- was construed as a quantity located on a vertical scale. In this case, the expert articulated : If it [ceramic] is an insulator, then they both act as insulators -because you've sealed both of them- and therefore the two would not have ... they would have cooled down, but they would not have basically cooled down to the same level. While saying "they would have cooled down", the participant gestured with his right hand in a downward straight vertical movement. This revealed that temperature/hotness is metaphorically construed as a quantity located on a vertical scale: more coolness is up, less is down. Consequently, this gesture doesn't reveal an ontological categorization of the heat concept and was not included in the analysis of data in this thesis.

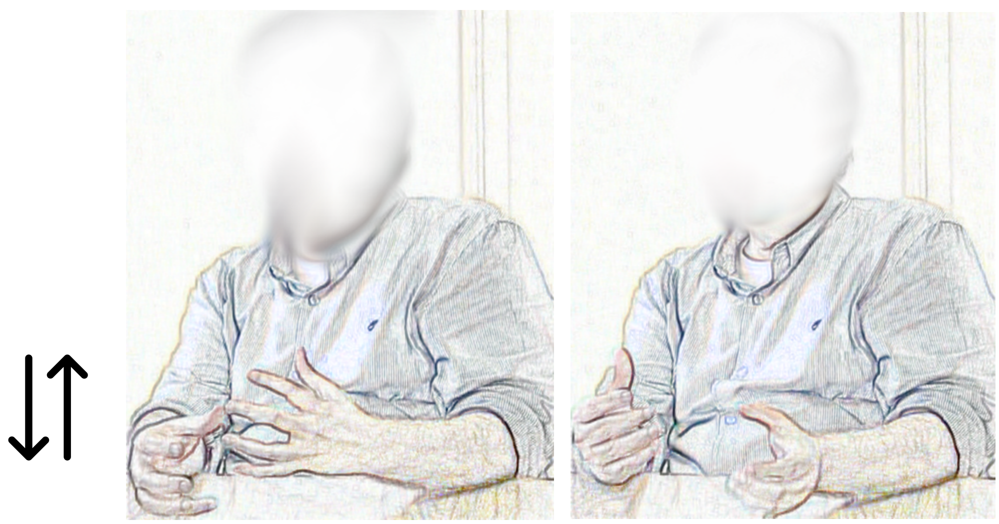
APPENDIX H

ILLUSTRATIONS OF EXAMPLES OF CONCURRENT GESTURE-SPEECH PAIRS

This appendix presents examples of how concurrent gesture-speech pairs were analyzed to address the third research question. These are instances where a speech predicate is accompanied by the production of one or more gestural predicates. This is so since more than one gesture may occur in one phrase (Goldin-Meadow, 2005; McNeill, 1992). Thus, given the nature of gestures, it is possible to have more than one gestural predicate produced with one verbal predicate. This aided in identifying consistent matter pairs, consistent process pairs, and inconsistent pairs. The following are illustrations of concurrent gesture-speech pairs produced by novices and experts.

<table>
<tr><td colspan="3">Examples of Consistent Matter Gesture-Speech Pairs</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Speech</td><td>Whereas in [metal rod] B its much weaker for it to sustain the heat being applied to it.</td><td>Supply, Matter</td></tr>
<tr><td>Gesture</td><td>The physical referent is embodying a forward jumping movement two times. The contextual topic is less dense metals doesn’t allow heat to stay/remain (i.e., sustained) in the metal rod. Thus, heat is metaphorically construed as a substance that is supplied by a source and has a path in which the denser the metal the more heat is sustained in it.</td><td>Supply, Matter</td></tr>
<tr><td colspan="3"></td></tr>
<tr><td>Speech</td><td>It [Styrofoam cup] is an insulator (a), it will not allow heat to pass easily (b) like the ceramic mug.</td><td>Move, Matter</td></tr>
</table>

Gestures	(a) The physical referent is an object that is bounded. Contextual topic is heat being insulated/trapped in the mug. Thus, heat is metaphorically construed as something that is contained.	Contain, Matter
	(b) The physical referent is an object moving inwards. Contextual topic is heat passing easily in ceramic mug more than in Styrofoam. Thus, heat is metaphorically construed as a moving substance.	Move, Matter

Examples of Consistent Process Gesture-Speech Pairs		
		
Speech	*So, there is no exchange of mass. The only thing exchanged is energy between body A and B*	Transfer, Process
Gesture	The physical referent is the opposite up and down movement of two objects that are being balanced. The contextual topic is the exchange of energy between A and B upon being in contact. Thus, the hand movement embodies the metaphor Equilibrium As Balance where	Equilibration, Process

	thermal equilibrium -i.e., energy exchanged- is construed as physical balance between two objects being located at the same level of axis. Also, it is construed to be a Location On A Vertical Line and Change in Quantity is Change in Location In Space: More Energy Is Up And Less Energy Is Down. This is evident in the coordination of the up and down movement of both hands: what an object loses energy the other gains.	

Examples of Inconsistent Gesture-Speech Pairs		
		
Speech	*There will be exchange of energy but not mass.*	Transfer, Process
Gesture	The physical referent is holding an object using both hands. The contextual topic is exchange in heat energy between two cubes due to temperature difference. Thus, energy is metaphorically construed as an object that is held in the hands.	Object, Matter

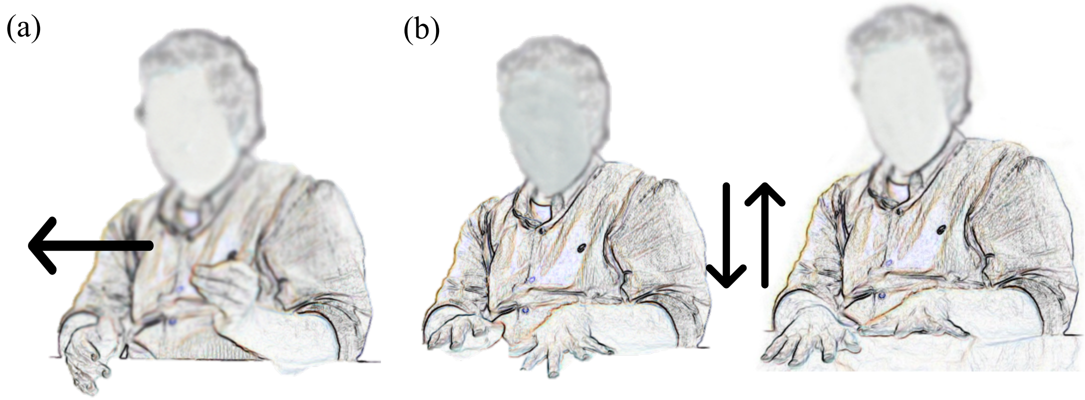
		
Speech	*Then the ambient light the smaller it is (a) the more the peak, the more you are able to detect (b) whether the peak is coming from the bulb will be invisible, will be detectable.*	SystemWide, Process
Gestures	(a) The physical referent is something moving downwards. The contextual topic is ambient light being smaller. Thus, the hand movement reveals metaphorically construing light as a quantity located on a vertical scale where more light is located up and less is down.	Quantity, Matter
	(b) The physical referent is something moving in an arc motion to the outside two times. The contextual topic is light being detectable. Thus, the outward movement reveals	Contain, Matter

	metaphorically construing light to be contained. The iterative movement reveals construing the more the contained light is moving outside the container, the more it is detected	

However, another challenge faced when analyzing concurrent gesture-speech pairs which was in judging whether a pair reveals in/consistencies knowing that some of the pairs included both matter and gestural predications. Thus, in the analysis of such pairs, we opted to be conservative when judging whether a pair is in/consistent. That is, if a verbal predicate has co-occurred with more than one gestural predicate where each gestural predicate corresponds to a different ontological category, then we opted to choose the position that does not favor the theoretical position of the researchers. It shall be noted, there are three gesture-speech pairs that revealed such pattern of predications, and they were analyzed similarly.

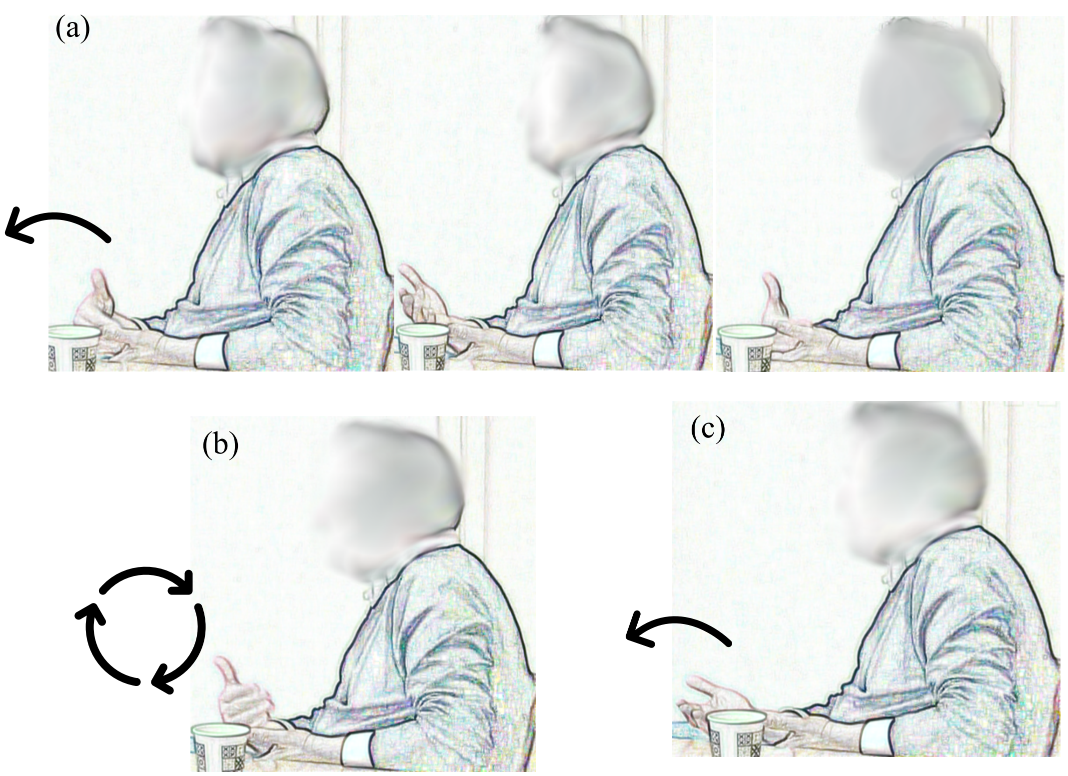
To elaborate, the following is an example from an expert protocol in which the participant was explaining energy exchange between two bodies occurring due to thermal equilibration. In this case, the participant stated: One is hotter so the heat will go from the higher to the lower until they reach equilibrium and they will have same temperature. This was considered as a process predicate. But also, the participant produced two other gestural movements. First when saying “the heat will go” the participant gestured in a straight horizontal movement from left to right. This gestural movement reflects construing heat as a moving substance. Then when saying “until they reach equilibrium” the expert produced a balance up and down movement using both hands: this gesture was considered as equilibration, process predicate. Thus, on the one hand, the verbal modality reflects ontologically categorizing heat as a process. On the other hand, the gestures produced reveal ontologically categorizing heat as *both* matter and process.

Consequently, the produced pair by experts was considered as revealing a *consistent process* ontological categorization of heat concept.

		
Speech	*One is hotter so the <u>heat will go (a)</u> from the higher to the lower until they r<u>each equilibrium (b)</u> and they will have same temperature*	Equilibration, Process
Gestures	(a) The physical referent is straight horizontal movement. The contextual topic is heat moving from container that is hotter than the other. Thus, heat is metaphorically construed as a moving substance.	Move, Matter
	(b) The physical referent is opposite up and down movement of two objects that are being balanced. The contextual topic is thermal equilibration. Thus, the hand movement embodies the metaphor Equilibrium As Balance where thermal equilibrium is construed as a physical balance between two objects being located at the same level of axis. Also, heat is construed as a quantity located on a scale where the change in quantity	Equilibration, Process

	represents change in location in space: More Is Located Up and Less Is Located Down. This is evident in the coordination of the up and down movement of both hands.	

Another example was evident in E2's protocol in which the participant was explaining light detection during daytime and night. In this example, the verbal modality reveals conceptualizing light as a process (systemwide) in which the detection of light is constrained by a mathematical equation. In parallel, this phrase has three cooccurring gestures: the first gestural movement reveals a matter predicate while the other two movements reveal a process predicate. As such, we opted to consider this gesture-speech pair as providing evidence for consistency in the use of process predicate rather than evidence of inconsistency.



Speech	*If your ambient light <u>is greater or equal (a) then (b)</u> <u>the ambient light</u> (c)…then you will not detect it.*	SystemWide, Process
Gestures	(a) The physical referent is something moving forward on a linear scale. The contextual topic is ambient light having numerical variation: greater or equal. Thus, light is metaphorically construed to be a quantity located on a scale: the greater the amount of light the further it is from the body.	Quantity, Matter
	(b) The physical referent is something moving repetitively (x2) in cyclic motion. The contextual topic is light being detected based on its variation. Thus, the cyclic motion reveals a process of MACHINE: input is the quantity of ambient light, and output is light detection.	SystemWide, Process
	(c) The physical referent is an object moving from left to right as if being is produced. the contextual topic is light detection depending on the variation of quantity. Thus, the straight movement reveal metaphorically construing light detection as A MACHINE: the output "what is given "is light detection	SystemWide, Process