Spring 5-11-2018

Effects of a Green Chemistry Laboratory Design on First- Semester General Chemistry Students' Transformative Experiences in Chemistry

Lurea Joan Doody

EFFECTS OF A GREEN CHEMISTRY LABORATORY DESIGN ON FIRST-SEMESTER GENERAL CHEMISTRY STUDENTS' TRANSFORMATIVE EXPERIENCES IN CHEMISTRY

A Dissertation

Submitted to the School of Education

Duquesne University

In partial fulfillment of the requirements for

the degree of Professional Doctorate in Educational Leadership

By

Lurea Joan Doody

May 2018

EFFECTS OF A GREEN CHEMISTRY LABORATORY DESIGN ON FIRST-SEMESTER GENERAL CHEMISTRY STUDENTS' TRANSFORMATIVE EXPERIENCES IN CHEMISTRY

By

Lurea J. Doody

Approved March 14, 2018

Amy Olson, Ph.D.
Assistant Professor
Department of Educational Foundations And Leadership
Duquesne University
(Committee Chair)

Dr. Rick McCown, Ph.D.
Professor of Education
Pierre Schover, C.S.Sp., Endowed Chair in Mission
Duquesne University
(Committee Member)

Marietta Wright, Ph.D.
Associate Professor of Biology
Department of Biology
Waynesburg University
(Committee Member)

Cindy Walker, Ph.D.
Dean, School of Education

Connie Moss, Ed.D.
Chair, Ed.D. in Educational Leadership

ABSTRACT

EFFECTS OF A GREEN CHEMISTRY LABORATORY DESIGN ON FIRST-SEMESTER GENERAL CHEMISTRY STUDENTS' TRANSFORMATIVE EXPERIENCES IN CHEMISTRY

By

Lurea J. Doody

May 2018

Dissertation supervised by Amy Olson

The purpose of this study was to understand if a green chemistry laboratory design facilitated students' transformative experiences in a first-semester general chemistry course for science majors. The study population consisted of 18 college students enrolled in the course at a small, rural, mid-Atlantic university. Traditional chemistry laboratories were replaced with three signature green chemistry laboratories over a period of 6-weeks at the end of the spring semester. Impact data were collected pre- and post, of the three labs using the Transformative Experience Questionnaire (TEQ) surveys. Open ended guided reflection questions were coded for elements of transformative experience (TE): expansion of perception (EP), experiential value (EV), and motivated use (MU). Process data were also included to provide contextual understanding of the impact data. Results indicate that each lab supported students’ transformative experiences and there is evidence to suggest that students’ TE increased modestly across the 6-week green chemistry laboratory experience. The experiential value (EV) element of transformative experience was most supported by the green chemistry laboratories. These findings suggest that a green chemistry laboratory design has potential to facilitate transformative experiences in chemistry for this population of students. Possible long-term effects include student motivation and retention in STEM fields of study.

DEDICATION

This work is dedicated to my son Aengus, my husband Bobby,

and to those we lost along the way.

"I stand here on the summit of the mountain. I lift my head and I spread my arms.

This, my body and spirit, this is the end of the quest.

I wished to know the meaning of all things.

I am the meaning. I wished to find a warrant for being.

I need no warrant for being, and no word of sanction upon my being.

I am the warrant and the sanction.

Neither am I the means to any end others may wish to accomplish.

I am not a tool for their use. I am not a servant of their needs.

I am not a sacrifice on their alters."

Ayn Rand, Anthem, 1938

ACKNOWLEDGEMENT

This work would not have been possible without the support, patience, and endurance of my colleagues, friends, and family. I am indebted to my advisor Dr. Amy Olson, who demonstrated stalwart qualities throughout this process that I will continually strive for in my professional career. To Dr. Rick McCown, thank you for helping me understand my role in the system I want to improve. And many thanks to Dr. Marietta Wright for your calming presence and sisterly support. Working with you all has been a pleasure and a privilege. To my dear friend and cohort member, Dr. Eva Allen, thank you for restoring my faith in woman-kind. To my son Aengus and my husband Bobby, I hope my work did not cost us too much time apart. Others I would like to acknowledge include Dr. Connie Moss, Darlene Miller, Dr. Evonne Baldauf, Dolores Doody, Brian Steinmiller, Dr. Ida Holaskova, and Starbucks. And a special thank you to my mother, Elizabeth Quintana, who was a maverick in her profession as a teacher, and in her role as my mother.

TABLE OF CONTENTS

LIST OF TABLES

Chapter 1

In 1997, a groundbreaking study was published that revealed reasons why students switch out of their science, technology, engineering, and math majors (STEM) to non-STEM majors (Seymour and Hewitt, 1997). As a graduate student in science at that time, the study resonated with my personal feelings about STEM education, the physical sciences, and chemistry in particular. Their research found that high-performing students were just as likely to leave the STEM fields in the first two years as their ‘less able’ counterparts, and chemistry was consistently found to contribute to their attrition from the sciences altogether (Gasiewski, Eagan, Garcia, Hurtado & Chang, 2011; Horowitz, Rabin & Brodale, 2013; Seymour & Hewitt, 1997). Researchers confirmed what I had already suspected, that there is a lack of interest and persistence in introductory STEM courses because the standardized nature of the curriculum is not engaging (Gasiewski et al., 2011; Seymour & Hewitt, 1997). Lecture-based foundational courses are traditionally taught as a retrospective of abstract facts, affording a glimpse of coherence and purpose only to those chemistry majors who persist in further courses (Osborne & Dillon, 2008). More recent research shows that an inordinate number of students drop chemistry in the first year, which means they either have to retake the course or switch to non-STEM majors (Villafane, Garcia, & Lewis, 2014). Therefore, as a central part of any STEM major’s curriculum, chemistry can be understood as a critical barrier preventing students from STEM careers (Gasiewski et al., 2012; Villafane, Garcia & Lewis, 2014). Utilizing methods of practical measurement, this study tested a theory of action to improve these outcomes for general chemistry.

Persistence and Interest in STEM

Undergraduate students switch out of STEM courses in large numbers compared to their non-STEM college counterparts (Horowitz et al., 2013; Seymour & Hewitt, 1997; Villafane et al., 2014). Student attrition from these programs of study is often blamed on the academic demands that STEM courses place on the students (Eisenhart, 2016). However, Seymour & Hewitt (1997) found no substantial differences in academic preparation or performance between students who persisted in STEM or switched to non-STEM programs, nor did the students themselves attribute their choice to ability, preparation, or persistence (Seymour & Hewitt, 1997, as cited in Eisenhart, 2016). These findings suggest that students leaving STEM programs were highly qualified students who had initially made the choice to pursue a degree in science. Therefore, it would be misguided to assume that lack of interest and persistence in STEM is a simple issue of student ability or career choice.

To illustrate, Seymour & Hewitt (1997) conducted a landmark study which explored the reasons why some 'switchers', who were above-average ability undergraduates majoring in STEM programs chose to switch to non-STEM majors. In a three-year study involving seven higher education institutions, and more than 600 hours of ethnographic interviews with 335 students, they revealed four primary reasons for student attrition from the sciences: loss of interest, the belief that a non-science major would be more interesting, poor teaching by faculty, and the overwhelming pace and load of STEM curricula (Seymour & Hewitt, 1997; as cited in Eisenhart, 2016). Of the 23 different issues which emerged from their data, 16 referred to pedagogical effectiveness, assessment practices, and curriculum structure. Nearly 40% of the students in engineering, 50% in physical and biological sciences, and 60% in mathematics switched to non-STEM fields of study. Although they found no variable distinguishing between switchers and non-switchers, both groups consistently complained about poor pedagogy (Seymour & Hewitt, 1997, as cited in Eisenhart, 2016). Importantly, only 12.6% of the switchers cited conceptual difficulties, and *chemistry* was reported as a common barrier to progression (Seymour & Hewitt, 1997). Further, the study showed that the reasons students gave for changing to other majors were *shared* by those who chose to stay in the sciences. In fact, 17% of the STEM majors who did not switch over the course of the 3-year study reported they were planning on changing to non-STEM careers after graduation (Seymour & Hewitt, 1997). Consistent with these findings, Gasiewski et al. (2012) found that lack of engaging pedagogy in introductory STEM courses are inordinately responsible for students switching out of their science majors within the first two years (Gasiewski et al., 2012). Specifically, Gasiewski et al. (2012) contend that students switch to non-science majors because they envision all future science courses to be similar, courses which are not engaging or personally relevant to the student (Gasiewski et al., 2012, p. 19).

In the following sections, I present an argument for why students do not find foundational STEM courses to be engaging or personally relevant. First, attrition is framed as a positive, where gatekeeping and merit-based phenomenon make it seem like students are incapable when they may just not be interested or motivated to continue. Next, I explain how constructivism may act to support student attrition from STEM courses, and from general chemistry in particular. Then I explore the problem of relevance in chemistry education and how it relates to student motivation and engagement. Finally, I propose a theory of action which could potentially increase student retention in general chemistry through a context which leverages student perceptions of relevance and agency.

Intentional Gatekeeping

Framing attrition as a positive, gatekeeping and merit-based phenomenon make it seem like students are incapable when they may just not be interested or motivated to continue in chemistry. Gasiewski et al (2012) argue that fault lies within the 'gatekeeper' mindset, which "either explicitly or implicitly function to eliminate all but the 'top tier' students and champion the concept that 'scientists are born, not made'" (Tobias, 1990, p. 11, as cited in Gasiewski et al., 2012). STEM education propagates this mindset, because goals of STEM are driven by professional education associations like the National Science Teachers Association (NSTA) which is funded by large multinational energy corporations, representing the nation's political and economic agendas; not our students' individual science learning needs (Aikenhead, 2006; Rudolph, 2007). Whether viewing science education from a sociocultural (Lemke, 2000; Roth & Lee, 2004) or global feminist (Barton & Tan, 2007; Brickhouse, 2001) perspective, the political text inherent in the STEM curriculum is exclusionary and designed to promote the gatekeeper mindset through an elite agenda of a few; at the expense of the many (Aikenhead, 2000; Gaseiwski et al, 2012). Tan & Barton (2007) agree, "this situates science education as a means to an end- that of producing skilled labor for global STEM related industries, with specific emphasis on ensuring economic viability for the home nation" (Tan & Barton, 2007, p. 2). In all, this agenda acts to support what is referred to in the literature as a 'leaky pipeline' (Aikenhead, personal communication, 2014; Rudolph, 2014). The 'leaky pipeline' is a sifting and sorting system where only those students with world views harmonizing with this agenda are open to the acculturation that STEM programs wish to deliver (i.e., the cream will rise to the top). Science educators are tasked with, "providing worthwhile and genuine experiences for all students, while, serving as gatekeepers for national interests and for the integrity of the discipline"

(Aikenhead, 2000, p.15). Too often, the gatekeeper mindset prevails, thereby arresting students' interest and persistence in science. In light of these understandings, there is a growing contingency of researchers and educators who are choosing not to align with STEM objectives by placing more emphasis students' personal development to increase student interest and persistence in science related subjects (Van Aalsvoort, 2004; Heddy & Pugh, 2015; Heddy & Sinatra, 2013; Feierabend & Eilks, 2010; Lemke, 2001; Movahedzadeh, 2011; Penuel, 2014; Roth & Jornet, 2014; Stuckey, Sperling, Mamlok-Namman, Hofstein, & Eilks, 2014; Roth & Lee, 2004; Rudolph, 2014a). It is believed that a more humanistic agenda may increase student interest and persistence in STEM because emphasis in on the value of science to the individual, rather than the value of the individual to science.

Constructivism and Gatekeeping

The way science content is taught may also contribute to students' negative perceptions of introductory STEM courses. The referent for teaching in science is firmly situated in the philosophy of constructivism (Lorsbach & Tobin, 1995). The constructivist epistemology establishes that students must construct their own knowledge by using their existing knowledge as a scaffold for new learning (Bybee, 2002). Through a process of information assimilation and accommodation, students learn by restructuring their pre-existing ideas in order to evaluate new information and solve problems through the negotiation of that new and existing information. Sometimes referred to as a 'personal paradigm shift', learning is said to occur when the student persists with the higher-order task of making sense of counter-intuitive, or perplexing ideas that resist their ordinary sense-making attempts (Fisher & Taylor, 1997).

However, couched in constructivist science rhetoric is the assumption that students have autonomy over their own thinking (Aikenhead, 2006; De Boer, 2000). This constructivist pretense means that students are encouraged to construct concepts as long as they come up with the *required* concepts, rather than their own (Aikenhead, personal communication, Nov. 20, 2015). Using an example from my own practice, inquiry-based laboratories are designed to facilitate students' scaffolding experiences, but the performance outcomes are dictated by standardized scientific facts which do not lend themselves to evaluation or deliberation. Poignantly, Dewey (1944, p. 219) said this of science:

> [Science] is like all knowledge, an outcome of activity bringing about certain changes in the environment. But in its case, the quality of the resulting knowledge is the controlling factor and not an incident of the activity. Both logically and educationally, science is the perfecting of knowing, its last stage.

That is, more than any other discipline, science is held to impossible standards, and one of those is content standardization (Kuhn, 1962; De Boer, 1991). While this pretense contributes to what makes science a powerful tool, it also acts to whitewash established meanings, where they have been 'laundered of contradiction, contestation, and ambiguity' before the student interacts with them (McClaren, 2015). Thus, the 'resulting knowledge' is often presented and perceived in this sterilized context. This encourages "rote and performance learning rather than mastery learning for understanding" (Osborne & Dillon, 2008, p. 15). In this light, constructivist teaching which focuses on the construction of knowledge, not the quality of students' experiences with the content, limits the potential for personal transformation to occur

(Hadzigeorgiou, 2016). Certainly, I am not suggesting that educators and students dismiss what is already ‘known’, but there has to be a balance between the knowing from the past and the design for future learning (Dewey, 1938). Thus, researchers are beginning to explore ‘a new kind of empiricism’ in science education which seeks to reclaim the aesthetic value of the content to improve the quality of the students’ experiences in science (Hadzigeorgiou & Shultz, 2014, as cited in Hadzigeorgiou, 2016; Pugh, 2011; Wong, 2002). It is believed that shifting the focus to the aesthetic value of the content improves the quality of students’ experiences in science because they are afforded the opportunity to evaluate and deliberate the value of what they are asked to learn constructively.

Chemistry and STEM Attrition

Chemistry is an entry point to the bigger problem of interest and persistence in STEM because it is an exemplar of the ‘gateway course’, in which all students are required to take foundational chemistry in order to proceed in STEM majors and careers (Belt, Leisvik, Hyde, & Overton, 2005; Ferrel & Barbera, 2015; Gasiewski, Eagan, Garcia, Hurtado & Chang, 2012; Villafane, Garcia & Lewis, 2014). And, it has been found that negative experiences in the introductory chemistry course contribute to student attrition from the sciences altogether (Horowitz, Rabin & Brodale, 2013; Seymour & Hewitt, 1997; Watkins & Mazur, 2013). Most of the students enrolled in a general chemistry course are not chemistry or chemistry education majors; rather, they are majoring in biology, environmental science, forensic science, pre-medicine, exercise science, engineering, or are undeclared science majors (Ferrell & Barbera, 2014; Gasiewski et al., 2012). It goes without saying that chemistry is a perennially unpopular course, and students frequently have negative perceptions of chemistry as being difficult, cold, abstract, and boring (Eilks & Hofstein, 2015; Kurbanoglu & Aikin, 2010; Lemke, 2000; Osborne, Simon & Collins, 2003; Seymour & Hewitt, 1997). Even students who say they like chemistry and do well in it share some of these negative perceptions or are at best, apathetic about the subject (Ferrell & Barbera, 2015; Garcia, Chang, & Hurtado, 2012; Hofstein & Mamlok-Naaman, 2011; Seymour & Hewitt, 1997). Moreover, many students do not understand how chemistry is relevant to their personal goals, so they give up on it, or give up trying to understand it (Holbrook, 2008; Osborne & Dillon, 2008; Taber, 2015). This is noted in Farrell and Barbera (2015) who state that “the combination of content difficulty and the fact that most students are fulfilling a credit requirement for their non-chemistry majors generates an interesting classroom environment for the introductory-level chemistry course” (Ferrell & Barbera, 2015, p. 318). Some authors suggest that attention to the personal goals of each individual student is an impossibility and reinforce the narrative that chemistry must be taught as a ‘general’ discipline that does not intrinsically relate to any major other than chemistry (Holbrook, 2005).

As the first course in a sequence designed to train future chemists, there is an extrinsic focus on the value of foundational chemistry for the next chemistry course, which some students may not need. Most foundational chemistry courses encourage “rote and performance learning” to prepare students for a chemistry degree, rather than “mastery learning for understanding” (Osborne & Dillon, 2008, p. 15). This makes the content in foundational chemistry the scaffolding for future chemistry learning in a degree sequence. In consequence, general chemistry is often perceived as a course which is propaedeutic- as having meaning only to serve the next course in the sequence, or as a graduation requirement (Gasiewski, Eagan, Garcia, Hurtado, & Chang, 2012; Roth & Lee, 2004). In point of fact, this perception and propagation of chemistry is mis-educative in that it removes liability from both the instructor and the learner to fully engage in learning experiences (Dewey, 1938, p. 49). As an instructor, I admittedly fall back on the promise of a concept's distal importance to the next course in the sequence when other motivational efforts fail. This palliative strategy may work for some students but using outcomes like these as incentives relegates learning to be 'accidental' in the course of the next academic attainment (Dewey, 1938). For others, it generates a 'lust for completion' which may register on performance outcomes; often though, this is at the expense of student engagement with the content (Hadzigeorgiou, 2016; Roth & Lee, 2004; Roth & Jornet, 2014).

In addition, the ways in which colleges have treated foundational chemistry has made it challenging to teach constructively. Passing high school chemistry, or even taking high school chemistry, is not a prerequisite for general chemistry, nor is it an admission requirement at most colleges and universities. For instance, in my general chemistry course for science and science education majors, there may be students with educative and mis-educative (Dewey, 1938) chemistry experiences from home school and cyber school environments, public and private school general chemistry classes, advanced placement or college credit chemistry courses, and those with no chemistry experiences at all. This not only complicates scaffolding instruction, it complicates understanding data related to research in chemistry education.

For example, Ferrell and Barbera (2015) contend that incongruent data result when students entering a course with strong chemistry backgrounds interpret questions related to self-efficacy. They found that those students with more superficial understandings of the periodic table may have an inflated sense of self-efficacy because they interpret a question such as, *How well can you describe the properties of elements using the periodic table?* as one referring to a simple view relating to the number of protons, neutrons, and electrons. Students with stronger chemistry backgrounds may be thinking more deeply about periodic trends of reactivity (e.g., ionization energy, electronegativity, or atomic radius) and respond with a deflated sense of self-efficacy for that item, thereby making trends in self-efficacy difficult to use when evaluating novel approaches to instruction in a foundational chemistry course (Ferrell & Barbera, 2015, p. 332). This is important to consider, because there is a resounding call in the literature for novel approaches to instruction to make chemistry more relevant for the learner (Belt et al., 2005; DeJong & Talanquer, 2015; Feierabend & Eilks, 2010; Gilbert, Justi, Van Driel, DeJong, & Treagust, 2004; Holbrook, 2005; Osborne, Simon, & Collins, 2003; Stuckey, Sperling, Mamlok-Namaan, Hoffstein, & Eilks, 2015). In the following sections, I will explain what the latest research suggests about what relevance could mean in chemistry education.

The Idea of Relevance in Chemistry

Many researchers argue that the common factor limiting student interest and persistence in chemistry is the perceived lack of relevance to students' lives (DeJong & Talanquer, 2015; Ferrell & Barbera, 2015; Hofstein & Mamlock-Naaman, 2001; Osborne & Dillon, 2008; Osborne, Simon & Collins, 2003). This seems counterintuitive to me, because chemistry influences nearly every aspect of one's life (e.g., foods, cosmetics, manufacturing, pharmaceuticals, clothing, air quality, and water quality), even eye sight is the result of chemical reactions! It is believed that improving student perceptions of content relevance is the most powerful way to improve student interest and motivation in chemistry (Aikenhead, 2003; Holbrook, 2005; Stuckey, Sperling, Mamlok-Naaman, Hofstein, & Eilks, 2013). However, as Aikenhead (2003) points out, stakeholders in science education have remarkably different opinions about the nature of relevance. Chiefly, he asks 'Who decides what is relevant, and relevant to whom'? To be sure, the idea of relevance in chemistry lacks clarity (Eilks & Hoffstein, 2015; Holbrook, 2008; Stuckey et al., 2013). For instance, some researchers use relevance and interest interchangeably where "relevance in science education is mainly related to the question of whether science education content accurately matches the students' real or perceived interests […] good reasons to consider 'relevance' and interest as consisting of overlapping but not identical ideas (Stuckey et al., 2013, p. 9). Others understand relevance in terms of value, regarding value and relevance to be conflated in the development of interest (Harackiewicz, Tibbets, Canning & Hyde; Hidi & Renninger, 2006).

In an effort to clarify the meaning of relevance in science education, Stuckey et al. (2013) analyzed 50 years of science education literature and found that relevant contexts should be regarded in terms of *consequences* which go beyond personal relevance to the learner, and "cover the ability of the individual to live in a modern society and to responsibly participate in it, as well as to contribute to the economy and its development in the field of science and technology-related business" (Stuckey et al., 2013, as cited in Eilks & Hofstein, 2015). Here, it is believed that context is both extrinsically and intrinsically motivating because the focus is on the *effects* (i.e., consequences) of the curriculum on the student, rather than the commodified needs of the stakeholders (Eilks & Hoffstein, 2015). To put it another way, the value of science to the individual, rather than the value of the individual to science.

Chemistry Relevance and Context

Relevance, from a pedagogical perspective, can be thought of as an issue of context (DeJong, 2006; Holbrook, 2005). To explain, Osborne & Dillon (2008) present an analogy that learning chemistry without a coherent context is similar to "being on a train with blacked-out windows", the student knows the train is going somewhere, but "the bigger picture only unfolds for those who stay the course to the end" (Osborne & Dillon, 2008, p. 15). Some authors suggest that context-based chemistry curricula have the potential to positively influence student interest and persistence in chemistry because they increase students' 'affective response' to, and 'predisposition for' learning through personally relevant contexts (De Jong, 2006; Holbrook, 2005; Lemke, 2000; Talanquer, 2013; Van Aalsvoort, 2004). However, others argue that context-based approaches in chemistry tend to result in positive affective development only, with little effect on chemistry learning (De Jong, 2006). Unfortunately, many chemistry curricula use hypothetical scenarios and analogies for contextualization that may not be in fact, relevant to the learners. For example, the blast furnace is often used when teaching about re-dox reactions: *The blast furnace, so when are you going to use a blast furnace? I mean why do you need to know about it?* (Osborne & Collins, 2001, p. 449, as cited in De Jong & Talanquer, 2015). Other reasons for their ineffectiveness are given in the literature such as: context may be confusing because the context is sometimes given after content, and that context is rarely part of content evaluation (Karpudewan, Roth, & Ismail, 2015). Additionally, contextual chemistry curricula often require learning the concepts first, then applying them; or, texts might use the context anticipatorily and students are expected to mediate their own understandings for application (Thiele & Treagust, 1992).

While it is understood that context driven chemistry curricula could potentially improve student interest and persistence in chemistry, existing research on how to improve has had very little impact on actual chemistry teaching practices (Gilbert, Justi, Van Driel, De Jong, & Treagust, 2004; Lazowski & Hulleman, 2016). Talanquer (2013) boldly suggests that these understandings have not translated into practice because of the 'monolithic' structure, and un-problematic perception of chemistry. In corroboration, many chemistry educators suggest that contextualizing chemical concepts within our current socio-scientific issues acts to problematize the discipline (Aikenhead, 1996; Holbrook, 2005; Lemke, 2000; Penuel; 2014; Roth & Lee, 2004; Rudolph, 2014; Van Aalsvoort, 2004). In fact, many researchers surmise that problematizing the discipline of chemistry in this way can positively influence the personal development of students, as *education through chemistry*, rather than *chemistry through education* (Holbrook, 2005; Penuel, 2014; Roth & Lee, 2004, 2007). It is thought that because science is often perceived as being value neutral, framing content within current socio-scientific issues creates a motivating sense of possibility (McClaren, 2015). However, by problematizing and politicizing the discipline of chemistry it becomes context specific, and a chemistry course intended for all STEM majors should be taught in a context which is valuable to all STEM majors.

Green Chemistry Context

Complementary to the humanistic science ideas proposed by Aikenhead and others (e.g., Costa, 1995; Gilbert, 2010; Ogawa, 1999), recent reform efforts in chemistry education suggest that framing science content within our current socio-scientific problems may help overcome domain-specific issues of student interest and persistence in chemistry (Aikenhead, 2003; Eilks & Hofstein, 2015; Holbrook, 2005; Hofstein & Mamlok-Namaan, 2011; Juntunen & Aksela, 2014; McClaren, 215). Researchers speculate that practices which actively involve students in the [making] of science increases their agentive, emotional, and epistemic cognitive engagement through the behavioral component of participating in globally beneficial practices (Sinatra et al., 2015). Within this movement, Green chemistry (GC) is a progressive and optimistic philosophy of chemistry education that unifies the content in chemistry through the collective purpose of sustainability. Using sustainability principles as a framework for practice, GC offers a primary, context based, in-practice approach to teaching chemistry (Feierabend & Eilks, 2010; Penuel, 2014). Initially GC was developed in the early nineties in response to industry needs for greener products and procedures. The principles were designed to be used by chemists and chemical engineers as a way to evaluate practices through the lens of environmental sustainability. Essentially, the 12 Principles of GC are guidelines designed to minimize the product of the risk equation (e.g., risk = hazard x exposure) both locally and globally. The principles were developed by Anastas and Warner (2000) to address the fact that chemistry is the cause of every environmental problem in existence (Freiraband & Eilks, 2010). They wrote the first book on green chemistry with the optimistic assumption that synthetic chemists did not want to harm the environment, they just did not have access to safer alternative processes and procedures that would be economically and environmentally compatible (Warner, personal communication, July 14, 2017). Anastas and Warner (2000) define green chemistry as "the utilization of a set of principles that reduces of eliminates the use or generation of hazardous substances in the design, manufacture and application of chemical products" (Anastas & Warner, 2000, p. 11). In other words, rather than waiting to remediate problems at the end of production, the principles are designed for primary pollution prevention at the source. In their optimistic view, chemists want greener practices, but it is estimated that of the [80% of benign industrial chemical practices that have been discovered to date, only 6%] have been effectively operationalized to meet the high demand from industry. This fact alone is thought to motivate students because it emphasizes the need for creativity and innovation in chemistry (Warner, personal communication, July 14, 2017).

The high demand from industry for greener products and processes instigated a movement in higher education to offer courses in green chemistry which continues to grow (Braun et al., 2006). As a relatively new idea in the educational literature, there are not many studies that have been specifically designed to understand how a GC context influences motivation and engagement in chemistry. Some researchers claim that a GC context facilitates students' personal development as education through chemistry, rather than chemistry through education, by emphasizing the socially mediated context of sustainability (DeJong & Talanquer, 2015; Sjostrom, Rauch, & Eilks, 2015; Taber, 2015). Other research claims that teaching chemistry in a GC framework produces positive gains in both student achievement and motivation because students feel 'empowered' by the local approach to a global problem (Karpudewan, Ismail, & Roth, 2012). In line with both of these perspectives, a GC context is thought to leverage student perceptions of agency because the outcomes, or consequences of learning, are personally relevant to the student (Eilks & Hofstein, 2015; Sevian & Bulte, Sjostrom, Rauch, & Eilks, 2015; Stuckey et al., 2013). Put another way, the 'act locally, think globally' ideas inherent in green chemistry can be utilized to increase student perceptions of personal agency. If students understand they can influence the consequences of chemistry through their actions, their sense of personal agency increases, and dependence on the proxy agent may decrease (Bandura, 2007). This holds far reaching benefits that has the potential to cyclically reinforce positive changes in student motivation and engagement in STEM.

Unlike other context-based curricula, GC is relevant in terms of students' experiences before, during, and after college, which is thought to expand student perceptions and world views beyond the lab (Mandler, Mamlock-Naaman, Blonder, Yayon & Hofstein, 2012). GC is not presented as an intervention or add-on course, but as "a new way of thinking about science in a responsible manner so that the lives of future generations are not compromised by today's actions" (Karpudewan, Ismail & Roth, 2012, p. 121). This intentional design embeds optimism and agency in the context because students are actively working on prevention of environmental problems in a primary context through their coursework (Giamellaro, 2014; Penuel, 2014).

Usually, discussions about agency around issues of sustainability refer to the proxy agents, or the 'technoscientific solutions' rather than people (Hufnagel et al., 2017). The GC perspective shifts that agency back to the individual. In this way, students are placed in the work, and in doing so, they are working toward the design of more socially just futures (Penuel, 2015; Roth & Lee, 2007). In accordance with this agentive perspective, the Next Generation Science Standards (NGSS) include engineering design elements for sustainability across all science curricula (Hufnagel, Kelly, & Henderson, 2017). Inherent to the design element of the NGSS is the idea that students are working towards solving real-world scientific design challenges through their coursework, or science *in practice* rather than science *as practice,* "integrating understanding [of] the ideas of science with *engagement* in the practices of science" (NRC, 2012, p. x, as cited in Sinatra et al., 2015, emphasis in original). Penuel (2014) argues that, "if we want to see how people use science and engineering as tools not just for social, cultural, and economic production but also for transformation, then we must choose settings where such transformations are evident" (Penuel, 2014, p. 8). In this case, students are actively involved in the 'making' of science by changing the way chemistry is practiced (Sinatra et al., 2015). This primary re-contextualization of the content may reanimate concepts into living ideas that require action (Dewey, 1938; Pugh, 2002).

Reframing the chemistry curriculum to be more intrinsically motivating, humanistic, and relevant should improve the interest and persistence problems. However, investigating the effectiveness of green chemistry requires investigating both content learning and measurement of affective motivational variables. This is difficult, because there are many ways to frame motivation and the existing literature points to problems with assessing some of the most common constructs (e.g., self-efficacy). It has also been found that intrinsically motivated students tend to be the most engaged because they adopt a mastery rather than performance learning orientation (Gasiewski et al., 2012; Pugh, Linnenbrink-Garcia, Koskey, Stewart, & Manzey, 2009; Ryan & Deci; 2000). But, as Deci and Ryan (2000) point out, it would be a pedagogical mistake for educators to rely on all of their students being intrinsically motivated.

Motivation for Chemistry Learning

Educational research on student motivation for chemistry learning is a huge topic because motivation varies not only by levels, the "energization of behavior", but also in orientation, the "direction of behavior" (Pintrich, 2003; Ryan & Deci, 2000). For example, a student can be highly motivated to learn biology and at the same time be apathetic about chemistry and vice-versa (Farell & Barbera, 2015). Or, a student can be highly motivated in chemistry when learning about the electronic structure of the atom and completely dis-engage with molecular orbital theory. Because of these understandings, it is often recommended that student motivation should be studied in highly specified contexts, rather than general domains (Pintrich, 2003, as cited in Farell & Barbera, 2015, p. 318; Ryan & Deci, 2000). For this study, I focus on motivation as agentive student engagement with concepts.

Motivational Interventions in Science

Motivational interventions in science can take on many forms, and there are many sound motivational theories in the literature from which educators can draw upon. Unfortunately, field studies on student motivation in science is relatively rare (Lazowski & Hulleman, 2016); even more so for motivation in college chemistry (Farrell & Barbera,2015; Talanquer, 2013). Recently, Lazowski & Hulleman (2016) conducted an extensive meta-analysis summarizing motivation intervention studies in science K-16. They argue that more than laboratory research, intervention field studies provide evidence about what can work in a specific setting versus what should work given a generalized theory (Lazowski & Hulleman, 2016). Defining motivation as the "energization and direction of behavior" (Pintrich, 2003 as cited in Lazowski and Hulleman, 2016), their meta-analysis investigated the effect sizes of 15 different motivational theories used in classroom interventions which were designed to enhance learning outcomes: achievement emotions, achievement goal theory, attribution theory, expectancy-value framework, goal setting, implicit theories of intelligence, interest theory, need for achievement theory, possible selves theory, self-affirmation theory, self-confrontation theory, self-determination theory, self-efficacy, social belongingness theory, and the model of transformative experience. The dependent variable defining student outcomes included performance measures, behaviors, and self-reports relating to motivation and engagement. In all, 74 published and unpublished intervention studies were reviewed which targeted motivational processes in 'ecologically valid educational contexts'; meaning they were natural treatments, natural settings and natural behaviors (Tunnell, 1977, as cited in Lazowski & Hulleman, 2016). Their analyses examined the average effect size of the motivation interventions as a whole and interpreted the effects of the 15 different intervention categories they surveyed. An overall moderate average effect size (d = 0.49) was reported on students' motivation for the more than 38,000 students included in the meta-analysis. Other educational outcomes such as student grades and course attendance were also found to be significant. However, their results showed no statistical or practical differences among the 15 motivational theories. Notably, they reported that transformative experience interventions had the highest average effect size (d = 0.74) compared with the smallest (d = 0.35) for social belongingness interventions. They cited study limitations such as overlap of constructs (i.e., studies exploring more than one motivational variable), intervention dosages (i.e., 10 minutes versus three weeks), and grade level differences (45% were post-secondary studies) as probable confounding variables. Nonetheless, these findings highlight the need for intervention field studies and reinforce the importance of motivation interventions on student outcomes.

Motivation and Engagement

Arguably, many of the academic measures included in the Lazowski and Hulleman (2016) meta-analysis of motivational interventions in science are conceptually overlapping constructs (Yeager, Bryk, Muhich, Hausman, & Morales, draft, 2017, p. 10). While the 15 motivational theories outlined in the study each have demonstrated merit in their own right, at their cores they seek to address the overarching problem of improving student engagement with the content (Lazowski & Hulleman, 2016; Sinatra, Heddy, & Lombardi, 2015). Engagement is a construct which can be thought of holistically as encompassing behavioral, cognitive, and affective dimensions of learning (Gasiewski et al., 2012), and refers to both "the quality and intensity of student involvement" (Fredericks, Blumenfeld, & Paris, 2004, as cited in Pugh, Bergstrom & Spencer, 2017, p. 16). It can hardly be contested that student engagement is central learning and is fundamentally important to nearly every desirable educational outcome including motivation (Fredricks, Blumenfled, & Paris, 2004, as cited in Koskey et al., 2016; Ryan & Deci, 2000; Reeve, 2013; Sinatra, Heddy, & Lombardi, 2015).

Often, engagement is a concept which is positively related to performance indicators such as student grades (Gasiewski et al., 2012), however as noted earlier, students can do well in chemistry and still choose to be disengaged with the subject (Farrel & Barbera, 2015). I argue that what I and many of my colleagues perceive as a lack of motivation for chemistry learning is actually an outcome of agentive student actions to not engage with the content because they have no desire to do so (Jegede &Aikenhead, 1999; Bandura, 2000; Eccles, 2005; Harackiewicz et al., 2014). In line with this position, Reeve and Tseng (2011) introduce a fourth dimension of engagement that is defined as a "student's constructive contribution into the flow of the instruction they receive" (Reeve & Tseng, 2011, p. 258). Agentic engagement is thought to connect the behavioral, cognitive, and emotional aspects of student engagement through students' personal involvement with the content (Reeve & Tseng, 2011). Agentic engagement can be thought of as both an indicator of motivation and deep conceptual learning, and as a mediator for those learning objectives (Reeve & Tseng, 2011; Sinatra, Heddy, & Lombardi, 2015). Where the behavioral, emotional, and cognitive aspects of student engagement are considered to be more or less a reaction to the learning environment, agentic engagement is a student-initiated dimension of engagement (Sinatra, Heddy, & Lombardi, 2015). In fact, Sinatra et al. (2015) contend that the agentive dimension of engagement is of particular importance to motivation in science because either implicitly or explicitly, students are asked to engage with concepts which require an epistemic form of cognition in which they have to evaluate evidence, understand uncertainty, and gauge the value of concepts without, in some cases, having direct experiences with them (Sinatra et al., 2015). While it is understood that the agentive dimension of student engagement subsumes one or more of the behavioral, emotional, and cognitive dimensions, researchers posit that this fourth dimension of student engagement aligns with Bandura's (2006) conception of the learning environment (Sinatra et al., 2015). Agentic engagement is a students' proactive attempt to make the learning environment more motivationally supportive for themselves by "taking achievement-fostering action that is something more than just behavioral, emotional, and cognitive engagements" (Reeve, 2013, p. 581). The 'more than' is understood to be student initiated-behaviors which support a mastery versus performance goal orientation in the learning environment (Sinatra et al., 2015). That is, if the student has no desire to learn the content, they do not take on the responsibility to activate their own learning by engaging with the concepts (Reeve & Tseng, 2011; Zimmerman & Schunk, 2011, as cited in Reeve, 2011).

Agentive Engagement and Autonomy in Science

If it is true that "to be an agent is to influence intentionally one's own functioning and life circumstances" (Bandura, 2006, p. 53), then it is reasonable to believe that some students resist agentively engaging with chemistry content because they do not find it personally relevant. Or, they may identify with anti-market and non-commodified epistemologies which do not align with STEM agendas (Aikenhead, 2000). To put a finer point on it, "outcomes are not characteristics of agentive acts, they are the consequences of them" (Bandura, 2001, p. 6). That is, if the student has the capacity (i.e., agency) and competence (i.e., efficacy) to act, but do not believe that their actions will make a difference, their motivation might suffer and they may choose not to engage with the content. This may be in response to an efficacy expectation, where the student does not perceive they have the ability to perform a particular skill; or it can be derived from an outcome expectation, the perception that their efforts will not make a difference (Bandura, 1977, 1981, 1986 as cited in Gecas, 1989). This abdication of personal responsibility is a selective disengagement strategy which serves to justify amotivational behaviors and displaces the student's personal responsibility for engaging with content (Bandura, 2007).

Where efficacy expectations refer to an individual's perceived competence to perform certain behaviors, outcome expectations refer to their environment (Gecas, 1989). Said another way, personal agency requires a socially brokered feeling of autonomy whereby the student is recognized as having rights to that agency (Hill, 1999). This is challenging, because traditional chemistry curricula are positioned as authoritative text, and students are afforded agency to learn only as far as they believe they are allowed (Aikenhead, 2000). That is to say, students may act with agency, but not as autonomous agents acting on their own motives because they perceive the 'canon of Western science' as being 'unresponsive' to their behaviors (Aikenhead, 2000; Gecas, 1989; Hill, 1999). In this case, the portrayal of traditional chemistry content as standardized 'knowing' that the student must enculturate, rather than evaluate, may diminish students' agentive engagement with the content because the concepts are not perceived by the student as being transformable (Aikenhead, 2000; Kuhn, 1962; Pugh, 2002).

After reviewing the literature, I have chosen an engagement construct as most relevant to this study because it is supported through the literature, predicts achievement, and it provides a theoretical framework for the initial problems of interest and persistence in chemistry. Recall that Lazowski & Hulleman (2016) found no difference in outcomes based on the type of motivational intervention used in science in their meta-analysis, but they did report that transformative experience had the largest effect size (Lazowski & Hulleman, 2016).

I have chosen to use transformative experience for this study because it is an operationalized motivation construct that embodies student engagement with concepts both insides and outside of class. The engagement in TE centers on student agency and is aligned with the political and pedagogical choices of a green chemistry intervention over a traditional one.

Transformative Experience as an Engagement Construct

Studies on motivation and engagement in science typically focus on "how engagement in enriching experience fosters conceptual development/change" with very little exploration of "how engagement with concepts fosters enriched experiences" (Pugh, 2002). The idea of conceptual engagement experiences improving motivation can be viewed as a fundamental aspect of a larger construct that warrants additional consideration: the transformative experience. Based on theories of transformational learning (e.g., Boyd, 2009; Dewey, 1938; Friere, 1970; Mezirow, 1991), transformative experience (TE) is an operationalized motivational construct which embodies the idea of a student's engagement with a concept leading to an enriched experience (Dewey, 1938; Heddy & Pugh, 2015; Pugh, 2002). Transformative experience is said to occur "when students apply classroom concepts to their everyday experience in a way that facilitates a change in perception of that experience and generates value for the concept" (Pugh, 2002, as cited in Heddy & Pugh, 2015). It is thought that when a student actively engages with the concepts their perception of the concept's personal relevance increases, which facilitates deeper learning and conceptual change (Heddy & Sinatra, 2013). Like other conceptions of engagement, the relationship between transformative experience and student motivation is not well defined. However, transformative experiences in science are thought to influence motivation by increasing enduring interest, enjoyment, and engagement with content by influencing students' everyday experiences in a personally meaningful manner (Girod, Twyman & Wojcikiewicz, 2010; Heddy & Sinatra, 2013; Heddy, Sinatra, Seli, Taasoobshirazi, & Mukhopadhyay, 2016). Specifically, transformative experience is linked to positive engagement outcomes such as positive emotions (Heddy & Sinatra, 2013, as cited in Heddy & Pugh, 2015), development of interest, academic career choice (Heddy & Pugh, 2015), the valuing of content (Heddy et al., 2016), and transfer of content learning to other settings (Heddy et al., 2016).

Where transformative learning is a grand 'personal paradigm shift' defined as, "a change that occurs in an individual's identity and/or personality that modifies how they interact with the world", a transformative experience is considered to be "a much more specific, directed change that occurs on the perceptual level" (Heddy et al., 2016). Said another way, a transformative experience is smaller change that may lead to transformational learning. Heddy and Pugh (2015) propose that even small transformative experiences provide desirable engagement outcomes, such as: positive emotions, development of interest, and career choices. They suggest that facilitating transformative experience is an operational way to promote transformative learning in that the aggregate quality of smaller shifts in perspectives may lead to grander transformative learning outcomes (Heddy & Pugh, 2015). In contrast to the traditional constructivist approaches to teaching a set body of knowledge in general chemistry, transformative experiences can be facilitated by reframing content as ideas and "possibilities that need to be acted on and tried out" (Dewey 1938 as cited in Pugh, 2002, p. 1103), rather than standardized information to be accommodated by the learner. Differentiating itself from other motivational constructs, transformative experience is a motivational construct developed within the purview of science education to address the unique challenges of motivation in science by emphasizing engagement and value of content beyond the performance requirements and outcomes of the course (Pugh, Bergstrom, & Spencer, 2017). A TE leads to "enaction in the learner, not simply awareness" (Caruana, Woodrow, and Perez, 2015). In other words, students learning for TE may demonstrate observable evidence that engagement with the concepts changed their thinking behavior or emotions with respect to phenomena in class, or in their lives outside of class.

The idea of transformative experience in science is not a new concept, but it is one that is difficult to capture in practice (Roth & Jornet, 2014). Roughly, transformative experience as a construct redirects our understandings of motivation to learn chemistry back to the Deweyan ideal of educative science learning that elevates the lived experience of the student by emphasizing the immediate and embryonic value of what we are asking students to learn in the present (Pugh, 2002). Elements of transformative experience include behavioral, cognitive, and affective components: motivated use (behavioral), expansion of perception (cognitive), and experiential value (affective), where all three must be present to be considered a transformative experience but not in equal measures (Pugh, 2011). Essentially, Pugh et al. (2010) posit that transformative experience leads to some change in how the student engages with their world outside of class. A few studies have been done investigating transformative experiences in the K-12 sciences (Pugh, 2002; Girod et al., 2010; Roth & Jornet, 2014), and in college biology (Heddy & Sinatra, 2013; Heddy et al., 2016), but there have been no studies published on transformative experience in general chemistry (Pugh, February 21, 2016, personal communication).

Green Chemistry and Transformative Experience

While it is understood that educators cannot cause directly cause transformative experiences to happen in their students, content can be presented in ways which may facilitate those experiences (Pugh, 2002; Wong, 2007). The Teaching for Transformative Experiences in Science model (TTES) offers two pedagogical elements which are thought to facilitate students' transformative experiences: the artistic crafting of standardized content into living ideas, and the emphasis on the personal relevance of the content (Heddy & Sinatra, 2013; Pugh, 2002). The TTES approach to teaching has shown promise for facilitating transformative experiences in science (Heddy & Sinatra, 2013; Pugh et al, 2010) because it reframes and reanimates the content into living ideas that require action (Dewey, 1938; Griod et al., 2010). GC is a primary context which embodies these elements where 'standardized content is reanimated into living ideas that require action', thereby this context may improve and motivation and engagement in chemistry (Pugh, 2004). From this agentive perspective, the quality of the learning experience depends on the individual buying into the socially authored objective learning conditions, because the individual becomes part of those conditions (Bandura, 2001; Dewey, 1938; Wong, 2007). Unlike other contextualized curricula, green chemistry makes performing experiments into an act of caring upon the world (Karpudewan et al., 2015). And, students are more open to transformative experiences when they are asked to learn things they believe are meaningful and worthwhile (Wong, 2007).

Theory of Action

Foregrounding general chemistry laboratory work in the 12 Principles of Green Chemistry (see, Appendix A) was the most fundamental way to initiate change in my chemistry education practice (Burmeister, Rauch, & Eilks, 2012). The 12 Principles of Green Chemistry were implemented through the laboratory section of General Chemistry over a period of six weeks. In an effort to control for quality and cohesiveness in the chemistry department and to minimize student risk, the lecture section for this course followed the department syllabus. The experiments used in this study were sourced from Beyond Benign (www.beyondbenign.org). These laboratories were chosen because the topics covered were the same as those found in a traditional general chemistry laboratory but practiced in an environmentally benign manner.

Context of the Study Population

General Chemistry is a two-semester course required for all STEM majors. This course is offered primarily to science majors where the intended sequence is that the first half of General Chemistry is taken in the fall semester and the second half of General Chemistry is taken in the spring. Students enrolled during the spring semester are not on the regular track because they are transfer or non-traditional students, they did not pass a pre-requisite math course, they did not test into the appropriate concurrent math course, or they failed to achieve a grade of C minus or higher in General Chemistry during the fall semester.

Usually, students who do not meet the math prerequisites must wait an entire academic year to begin the general chemistry sequence. Because General Chemistry is a two-semester course, students at most colleges and universities have to wait an entire academic year to 'catch up' by passing the prerequisite math courses before they can begin the general chemistry sequence. At the small University where the study took place, students were afforded the opportunity to take the first half of general chemistry during the spring semester. Although the spring General Chemistry section is not considered remedial, the population is considered 'at risk' for attrition. None of the students enrolled in the spring section of the general chemistry course were chemistry or chemistry education majors. Seven of the 18 students (39%) enrolled in the course did not take chemistry in high school.

I invited this unique group of students to test a theory of action that sought to understand if a GC context effectively reanimated standardized chemistry concepts in a way that leveraged personal relevance to facilitate students' transformative experiences in chemistry through a globally beneficial practice. Transformative experience was chosen as the motivational construct because it measures motivation as a student's agentive engagement with the concepts outside of class. Thus, the following research question was used to focus data generation:

> What is the evidence that green chemistry laboratory experiments support transformative learning experiences in chemistry?

The Transformative Experience Questionnaire (Koskey, et al., 2016; Pugh, et al., 2010) was utilized along with qualitative data generated through student reflections on each green chemistry laboratory experiment to reveal if there was evidence related to transformative experience in chemistry. Evidence of transformative experience was defined as: motivated use (MU), expansion of perception (EP), and experiential value (EV). The 27 Likert-type items on the questionnaire aligned with a continuum ranging from engagement with the content in the classroom to out-of-school engagement.

Measuring transformative experience quantitatively and qualitatively for the same activities provided a better understanding of the kinds of experiences which facilitated transformative experiences. The TEQ was designed to give a composite score for students' TE, and the reflection questions were designed to reveal evidence related to the elements of TE (EP, EV, and MU). Therefore, a convergent parallel mixed method design was utilized where quantitative and qualitative TE data were collected for the same activities (Creswell & Plano Clark, 2011). In this way, quantitative and qualitative data on transformative experience were collected and analyzed separately with respect to the research question; with data inference about evidence of transformative experience not occurring until the study ended.

Because there was no control group, this study is not considered an intervention by traditional research standards; however, it was built upon the premise that, "interventions are formal activities planned for a defined period, with a precise goal or desired change in mind, for a specific organizational setting" (Mintrop, 2016, p. 133). Following Mintrop's (2016) qualities of research-based interventions, process and impact data were collected and generated based on three signature GC laboratory experiments which replaced the traditional laboratory experiments. Pre/post-lab TE survey items were used to reveal evidence of transformative experiences across the 6-week green chemistry lab sequence and for each lab. Qualitative student TE reflections were collected post-each laboratory to investigate elements of TE with respect to each lab. A detailed outline of study procedures and their theoretical constructs can be found in Chapter 3.

To summarize, it appears to be well understood that there is a need to improve student persistence and motivation in chemistry. Existing research on how to improve student motivation in chemistry has had very little impact on actual chemistry teaching practices. Current research suggests that motivational interventions have the potential to positively impact student educational outcomes, which arguably, at their cores, seek to actively facilitate student engagement. Transformative experience is thought to be a holistic engagement construct which may positively influence motivation through agentive student engagement with concepts- and is a laudable goal in its own right. Although there has been research done on transformative experience in science, there have been no studies published on transformative experience in chemistry. This study sought to understand if there was evidence related to students' transformative experiences in chemistry by making the content more personally relevant through a green chemistry (GC) laboratory design.

Significance of the Study

Underrepresented groups are disproportionately affected by environmental pollution, health compromising foods (e.g., food deserts), and hazardous wastes (Barry, 2005; Bandura, 2002; Gorski, 2013; Millner, 2013). Importantly, Penuel (2015) found in his improvement work on social design experiments, these social factors present compelling science and engineering design challenges for those in education willing to recognize and address the systems responsible for delivering these unacceptable outcomes. In fact, the Next Generation Science Standards (NGSS) clearly call for crosscutting elements of design in the context of socio-scientific challenges like climate change (Hufnagel et al., 2016). Although the NGSS are typically applied to secondary education, colleges are responsible for educating the next generation of scientists, engineers, and teachers. And many researchers believe that higher education is situated to usher in a new level of understanding about the importance of sustainable development (Cortese, 2003). If there is evidence to support that the educational outcomes of green chemistry are as beneficial to students as traditional chemistry, why would anyone want to practice in the traditional paradigm? In this case educators, not scientists, could potentially cause a 'paradigm shift' in the way we practice science.

Science has always been slow to change, even in light of empirical evidence. To illustrate, Kuhn (1962) chronicled the history of science and the paradigm shifts which have taken place since the scientific approach to knowledge began over 400 years ago. In fact, the phrase ‘personal paradigm shift’ from Mezirow’s (1975) foundational work on transformational learning was borrowed from Kuhn (1962) who sought to understand how entire systems of scientific thought were able to survive in light of contrary evidence while others could change so drastically in an instant. Kuhn (1962) argues that while science itself is understood as an empirical approach to knowledge, it doesn’t always progress or change in light of new evidence. In other words, during what are called Kuhnian times of quiet, or what he refers to as ‘normal science’, scientists tend to make their data fit the reigning theory of their day. When confusion emerges, lines may be drawn but change is stunted by socio-political factors. It has only been in times of crisis that scientific revolution occurs and ushers in a new theory. When a revolution does occur, we make sense of new data; but more importantly, historical data is seen in new light (Tro, 2014, p. 322).

For example, Lord Kelvin, née William Thompson (1824-1907), was considered “a colossus, a megalith” (Burchfield, 1990, p. 107) in the scientific community during his time. His numerous accomplishments included establishing the science of physics, the metric system, and the second law of thermodynamics. These accomplishments gave him gravity among his peers, the government, and the general population. His popularity led to him being the first scientist elevated to the nobility as Lord Kelvin. It is certain that Kelvin was a well-respected scientist, but extollers aside, his assertions about the age of the 20-400 million- year old Earth were met with contention and debate in the scientific community. Geologists of the time were experiencing a paradigm shift towards Uniformitarianism and Darwin's Theory of Evolution was gaining momentum. The precepts of these complementary theories required an Earth that was much older than Kelvin's estimations. This debate caused better science- science that used more evidence than assumption. The general public, however, accepted Kelvin's ideas. His friend, Mark Twain, reflected the common opinion of the day "As Lord Kelvin is the highest authority on science now living, I think we must yield to him and accept his view" (Mark Twain, as cited in Burchfield, 1990). Kelvin's popularity, combined with the non-demonstrative evidence required for a 4.5-4.6 billion-year old Earth proved to be a difficult concept for the public to grasp. Even when his calculations were proved inaccurate, Kelvin's popularity kept his 20-400 million-year-old Earth in queue as part of the physics curriculum for more than 30 years. In light of the paradigm shift that followed, Kelvin's thermodynamic estimations were actually used as evidence supporting the 4.5-4.6 billion-year old Earth.

As Kuhn (1962) discussed in his book, dramas like this are at the heart of scientific revolutions. In fact, "competition between segments of the scientific community is the only historical process that ever actually results in the rejection of one previously accepted theory or in the adoption of another" (Kuhn, 1962, p. 8). This transformation is known as a paradigm shift. Climate change is irrefutable, as both demonstrative and non-demonstrative scientific evidence supports it (Bandura, 2007; Brown, 2008; Flannery, 2005; Gelbspan, 2004; Kennedy, 2005; Rudolph, 2007). Yet, it has been politicized to the point where many people think they can vote for or against it. I am not naïve enough to suggest that green chemistry being practiced in a general chemistry course will prevent environmental crisis on its own, but students are given the opportunity to recognize that the 'knowing' does not exist in contrived containers supplied by professional educators (Kuhn, 1962).

Chapter 2

This chapter begins by explaining the problem of personal relevance in traditional chemistry curricula and current relevance inspired context-based chemistry curricula. Then, I explain how a green chemistry context may increase student perceptions of personal relevance in chemistry through the social cognitive theory of agency. Next, elements of transformative experience are reviewed as they relate to agency and engagement. Finally, the potential for facilitating transformative experiences through a green chemistry context is discussed.

The Problem of Personal Relevance in Traditional Chemistry

Because traditional general chemistry courses are usually presented as being heavy in content and rigor, and low on personal value, many students perceive chemistry as being cold, abstract, boring, and too difficult (Eilks & Hofstein, 2015; Hofstein, Eilks & Bybee, 2011; Holbrook, 2005; Kurbanoglu & Akin, 2010; Osborne, Simon & Collins, 2003). As a result, the chemistry education literature is overwhelmed with studies and rhetoric for making chemistry education more relevant (Aikenhead, 2003; DeJong & Talanquer, 2015; Feierabend & Eilks, 2010; Holbrook, 2005; Hofstein & Mamlock-Naaman, 2001; Osborne, Simon, & Collins, 2003; Stuckey, et al., 2014). Ultimately, these colloquia suppose that content relevance will improve student engagement and motivation in chemistry. This is nothing new- the canon of science education reform literature has been calling for relevant science curricula for more than 100 years (Aikenhead, 2006; DeBoer, 1991; Stuckey et al., 2013; Kuhn, 1962). Still, most iterations of chemistry curricula are left wanting for meaningful learning, where content is "isolated from students' personal interest, from current society and technology issues, and from modern chemistry" (DeJong, 2006). Lemke (2001) agrees, "concepts taught in this way are relatively useless in life, however well they may seem to be understood on a test" (Lemke, 2001, p. 300). In other words, chemistry education remains content-driven, reflecting the reliability of the knowledge base while simultaneously undermining its relevance and tentative nature (Holbrook, 2005).

Context-Based Approaches in Chemistry

Many researchers argue that the perennial unpopularity of general chemistry can be overcome through relevance inspired context-based approaches (DeJong, 2006; Hofstein & Mamlok-Naaman, 2011; Osborne & Dillon, 2008; van Aalsvoort, 2004; Talanquer, 2013). However, literature pertaining to context-based approaches in college chemistry appear to be reserved for non-major or upper-level chemistry courses, not the foundational STEM major chemistry courses (Talanquer, 2013). Ideas for what context-based approaches in chemistry should look like essentially rely on a need-to-know approach such as Everyday Chemistry (Childs, Hayes, & O'Dwyer, 2015), which is a 'need-to-know' approach using everyday issues (i.e., genetically modified crops), activities (i.e., cooking), objects (i.e., smart phones), and health (i.e., medicine) to focus chemistry topics. Chemistry in the Community (American Chemical Society, 2006) is another 'need-to-know' approach that uses locally collected observations and data collection. However, these approaches are typically made for and used in secondary education and elective chemistry courses. Generally, they follow the traditional model of context-driven applications, as a 'cup to pour out the content' (Giamellaro, 2014). Some college curricula are presented in a context-related way, but these courses are usually reserved for upper level and highly focused courses such as physical chemistry (Belt, Leisvik, Hyde, & Overton, 2005). In all, these approaches have had limited success and chemistry continues to be a field that is commonly taught like it is a 'classic' (Anastas & Eghblai, 2009).

Some researchers argue that relevance inspired context-based approaches have had limited success in chemistry education because they are not presented as central to the curricula (DeJong, 2006); rather they are presented as 'a container to deliver content knowledge in' (Giamellaro, 2014). The content generally comes first, and the hypothetical or supplementary context application second (DeJong, 2006; Holbrook, 2005). Moreover, the context, while relevant to the instructor, or to society at large, may not be relevant to the students (DeJong & Osborne & Dillon, 2008; Talanquer, 2015). For instance, Osborne & Dillon (2008) provide an example of using the blast furnace analogy, a context which is often used to teach about reducing agents. This context may be relevant to the concept of redox reactions, but it is not a context relevant to most students' lives. Further, the size and scope of a general chemistry course and its importance to the sequence of future courses leaves little instructional time to delve into the anecdotal and 'real-life applications' side bars in text books where contextual applications are typically explored (Belt, Leisvik, Hyde, & Overton, 2005; Giamellaro, 2014; Gilbert, 2006; Holbrook, 2005; Horowitz, Rabin, & Brodale, 2013; Karpudewan, et al., 2015).

Defining Relevance in Chemistry

Researchers argue that the idea of relevance in chemistry lacks clarity: Does relevance mean that the student finds the concepts relevant to their everyday life, or is relevant for all students to have an understanding of chemistry so that they can cope with chemical concepts in everyday life (Childs, Hayes & O'Dwyer, 2015; Eilks & Hoffstein, 2015)? While both perspectives support the importance of content knowledge, they differ in their approaches to the processes of presenting chemistry in a context-related way. In the former, relevance refers to engagement with concepts because of their immediate familiarity to the student. For instance, using every day examples such as cosmetics, pharmaceuticals, and water quality. In the latter, relevance means that all students should understand the 'big ideas' in chemistry so that they can engage with technoscientific discourse as informed citizens. What is clear, is that students are more interested in learning chemistry content when the fundamental purpose of learning is directly related to their personal lives (DeJong & Talanquer, 2015; Osborne & Dillon, 2008; Osborne, Simon & Collins, 2003; Stuckey, Sperling, Mamlok-Naaman, Hofstein & Eilks, 2013). However, Taber (2015) warns that context-based approaches in chemistry assume that students are not motivated "by an epistemic hunger to make better sense of the natural world" (Taber, 2015, p. 95). In other words, teaching chemistry in a context-related way should not be done to simply placate the students who are not intrinsically interested, rather, it must also meet the needs of the students who are. Accordingly, many researchers contend that the fundamental purpose of relevance in context-driven approaches to chemistry must be understood and made explicit through the context, without 'watering down' the content (Holbrook, 2005; DeJong, 2006; DeJong & Talanquer, 2015).

DeJong and Talanquer (2015) ask important questions about the fundamental purpose of chemistry in regard to relevance: What chemistry content is relevant and to whom? As one of many stakeholders in this conversation, I would also ask *for what purpose*? Recently, it has been found that relevance in chemistry should be understood through a context of personal and societal consequences of learning for the student (Stuckey et al., 2013 as cited in Eilks & Hofstein, 2015). To explain, Stuckey et al. (2013) examined fifty years of literature referring to relevance to promote motivation in chemistry education. They found that the term ‘relevance’ was often conflated with other affective constructs such as meaningful, motivating, interesting, engaging, and important. Predominantly, they found that most research about relevance in chemistry education are actually studies on student interest (Stuckey et al., 2013). Certainly interest is an important first step for conceptual learning to occur, but relevance refers to being ‘closely connected’ to the concept, and arguably engagement (dictionary). Further, they found that the many stakeholders in chemistry education each had their own unique interpretations of relevance depending on their commodified interests (Aikenhead, 2003, as cited in Stuckey et al., 2013).

By understanding relevance through the aims of education in general and science education in particular, they found that relevance must include a societal dimension that includes both present and future real-life effects (i.e., consequences) on the student (Stuckey et al., 2013, as cited in Stuckey et al., 2015). Based on this broad analysis, they suggest that by focusing on consequences, ambiguous stakeholder intentions could be mitigated. In other words, science taught in this manner empowers the individual to learn for personal reasons rather than stakeholder purposes. Further, they argue that students are intrinsically and extrinsically motivated by a ‘consequences’ driven perspective of relevance because it shifts the focus to the ‘personal needs’ of the student (Stuckey et al., 2013, p. 3). Here, personal needs do not refer to course outcomes, rather, they refer to a compelling purpose for the student to either avoid negative, or produce positive, consequences of chemistry practice. It is believed that presenting chemistry content in this way generates a sense of anticipation, which is an important and often neglected aspect of engagement (Osborne & Dillon, 2008; Stuckey et al., 2013; Wong, 2007). Here, anticipation refers to the personal consequences for learning the concepts in chemistry, which implies students should learn for transferrable rather than generalizable skills in regard to society (Belt et al., 2005; Coll, Dalgety, Jones, & Slater, 2001).

Relevance Interventions in Science

Relevance interventions in science appear to work, but it is not clear how they work. To elaborate, Hulleman and Harackiewicz (2009) conducted a research study in which they looked at the impact of a 'relevance curriculum intervention' on students' interest and performance in science. In particular, they were interested in the students considered 'at risk' for being disengaged from school. In two randomized experiments with college students enrolled in an introductory psychology course, success expectancies and initial interest were measured pre-intervention. Using grades and post measurements, they found that the relevance intervention worked best for students with poor performance histories. However, the researchers noted that "little empirical evidence support[ed] the specific role of relevance in promoting optimal educational outcomes", finding most evidence to be "anecdotal or correlational" (Hulleman & Harackiewicz, 2009, p. 1410). That is to say, even though the authors found evidence of a positive relationship between the variables, they were not able to ascertain how the process worked; leading them to question, what was it about the relevance intervention that connected with the students? Chiefly, they argue that the relevance intervention facilitated the personal growth of students, stating that "making science courses personally relevant and meaningful may engage students in the learning process, enable them to identify with future science careers, foster the development of interest, and promote science-related academic choices (e.g., course enrollment and pursuit of advanced degrees) and career paths" (Hulleman & Harackiewicz, 2009, p. 1411). The authors speculate that the relevance intervention facilitated the students' perceptions of value for learning the content beyond the performance requirements of the course (Hulleman & Harackiewicz, 2009).

Personal Development as Relevant Chemistry Context

Many progressive studies call on research to understand and capitalize on the idea of focusing on students' personal development, as education through chemistry- rather than chemistry through education (Feierabend & Eilks, 2010; Holbrook, 2005; van Aalsvoort, 2004). Another way to look at relevance in chemistry then, is from the perspective that personal development can be mediated through context in chemistry (DeJong, 2006; Gilbert, 2006; Penuel, 2014; Roth & Lee, 2004; van Aalsvoort, 2004). Approached in this way, the discipline of chemistry has the potential to become an emancipatory context through which the student's personal development is privileged (Lemke, 2000; Penuel, 2014; Roth & Lee, 2004). When students connect traditional concepts with real-world contexts, personally meaningful learning can occur (Gilbert, 2006). This is noted in Holbrook (2005) who states that education through chemistry is "no more about learning the ways of the chemist any more than history is taught to become historians, or language is taught to become linguists" (Holbrook, 2005, p.3). Similarly, Van Aalsvoort (2004) sees the potential of focusing on students' personal development where, "chemical education, as part of education in general, prepares the pupil for participation in society" rather than training them to be disciplinary experts (van Aalsvoort, 2004, p. 1635). Although this view has been met with some 'sardonic resistance' in higher education (Bryce, 2010), there is a burgeoning body of literature linking more humanistic forms of science education to improved student motivation and engagement (Aikenhead, 2006; Bryce, 2010;

Burmeister, Rauch & Eilks, 2011; Feierabend & Eilks, 2010; Osborne & Dillon, 2008; Karpudewan, Roth & Ismail, 2015).

Contextual learning occurs in chemistry regardless of the applied context (Giamellaro, 2014; Roth & Lee, 2004). It has been shown that the way in which learning is situated is more important to the learner than the information to be learned (Dewey, 1938; Giamellero, 2016). Thought of in this way, students are learning in context whether the learning is applied to a contextual situation or not. The goal is for the student to be able to apply what was learned in context, *and* to resituate the learning when the context is different- in other words, students should be able to transfer their learning to new contexts (Dewey, 1938; Giamellaro, 2016; Roth & Lee, 2004). While there is a lot of literature in chemistry education pertaining to the learning environment, there are very few studies which focus on student learning experiences with chemistry concepts (Coll, Dalgety, & Salter, 2002). This is an important distinction to make, because learning experiences include student engagement with the concepts outside of class (Caruana, Woodrow, & Perez, 2015; Coll et al., 2002; Karpudewan, Roth & Ismail, 2015; Zimmerman & Bell, 2012). Too often, learning is studied in realtion to the learning environment, not the learning experience.

Primary and Secondary Contextualization in Science

Giamellaro (2014) explores the dichotomy between primary and secondary contextualization. In his paper, research findings support the idea that there are levels of contextualization in science learning, primary and secondary. Exploring the concept of contextualization from the learner's perspective, he found that there is little transfer between settings when the context is secondary because the student is "learning an abstract concept in connection with equally abstract, text-based context" (Giamellaro, 206, p. 7). Similar to Dewey's apprenticeship vision (1938), Giamellaro holds that "primary contextualization refers to first-hand, direct experience within contexts in which the content can be readily detected and applied in an authentic manner" (Giamellaro, 2016, p. 8). In his study, Giamellaro (2014) looked at two similar but distinct learning environments where one group of secondary ecology students were learning mammalian anatomy with a mammal dissection in the classroom, and the other group of students participated in a necropsy of a beached dolphin at a local aquarium. Again, the collateral learning (Dewey, 1938) was more impactful on the students than the lesson itself (Giamellaro, 2016). Not surprisingly, the students who got to go to the aquarium and participate in a dolphin necropsy were more engaged and outperformed the students conducting the mammal dissection in the lab. It can hardly be contested that these immersive experiences, or intentional contextualizations, are more educative than traditional classroom learning. Our minds are continuously processing context to make meaning of content, and thus context becomes a critical component of the learning environment and the learning experience. As Giamellaro posits, "A learning environment is imbued with context that either supports the learner to develop an understanding that is in keeping with the scientific communities of practice or to develop an understanding that is situated in other ways of knowing", to the contrary, "learning in an environment in which the learning goals are not reflected simply becomes nonsensically situated in the environment where the knowledge only has surface value" (Giamellaro, 2016, p. 4). Thereby, learning is often relegated to the learning environment rather than the learning experience. Clearly, there are pragmatic and economic reasons for why immersive experiences or intentional contextualizations like these are improbable for a general chemistry course- on a regular basis, if at all.

Penuel (2014) similarly sees an effective learning context as one that is ‘emplaced’, where learning occurs “not as practices isolated from their particular contexts, but located within a network of practices in a specific time and place” (Penuel, 2015, p. 11). In other words, the extant cultural dimensions that are determined by the time and place in which we find ourselves are compelling local contexts which rely on a global reality (Holbrook, 2005). Here, what students are asked to learn locally places them in conversation with a larger socio-scientific context, and in doing so, they are working toward the design of more socially just futures (Penuel, 2015; Roth & Lee, 2007). In line with other researchers, Penuel (2015) contends that situating learning in this way provides a sense of anticipation, which is an oft neglected aspect of engagement (Osborne & Dillon, 2008; Penuel, 2014; Wong, 2007). Expertly foregrounding his argument in the belief that science (and engineering) is inextricably linked with social responsibility and community development, Penuel (2014) surveyed studies where students were literally “transforming cultural and academic production” and therefore participating in social design experiments (Penuel, 2014, p. 8). He found that experiences in science which focus on pressing human needs, rather than training students to be ‘disciplinary experts’ motivates students to engage with the content because the consequences of learning are personally relevant to the student. Penuel (2014) argues that “learning inheres in such activities, not only because people access and make use of science knowledge and develop repertoires for participating in science and engineering practices, but also because participation in such activities transforms the ways that people imagine themselves and expands their possibilities for action” (Penuel, 2014, p. 2). In essence, Penuel (2014) insists that science education does not exists for the sole purpose of producing future scientists (i.e., do we teach history for the sole purpose of producing future historians?) rather, it exists to facilitate the personal development of the student. In other words, the 'universal value' of the content should be made explicit through the context (Osborne & Dillon, 2008; Penuel, 2014).

Context and Agency in Science

In a more recent study, Penuel (2015) also explores the dichotomy between primary and secondary context but does so by explaining the contextual differences of learning science *in* practice rather than learning science *as* practice- which is an important distinction to make with regard to the idea of *design*. A context for learning can invoke principles of design for students learning chemistry *in* practice through a compelling socio-scientific local issue, rather than *as* practice to train future chemists. Through the design element, the distal outcomes of learning in context also become purposeful beyond the more proximal performance goals (Burmeister, Eilks & Rauch, 2010). Importantly, students' perceptions of agency increase as a result (Penuel, 2014). However, many progressive educators remind that teaching and learning in context rather than with context can be 'messy' work, in that some outcomes for authentic work cannot be predetermined (Duschle & Osborne, 2012; Giamellaro, 2016; Penuel, 2014; Roth & Jornet, 2014; Roth & Lee, 2004). Further, researchers are concerned with "how to operationalize and measure engagement when students are participating in scientific and engineering practices" rather than simply learning *about* them (Sinatra, Heddy, & Lombardi, 2015).

Feierabend & Eilks (2010) proposed a similar philosophy of education through chemistry rather than chemistry through education. Understanding that the majority of students would not have a career in chemistry, they reoriented chemistry content as a problem in the socio-critical context of climate change. Their research showed that students responded with high levels of interest and motivation towards chemistry. Principally, they found that when using this context, students came to a more authentic understanding of science, in that *"science offers the basis for evaluations"* but, "*the evaluation has to be done by each person individually"* (Marks & Eilks as cited in Feierabend & Eilks, 2010, emphasis in original). They found that this context motivated students because students were afforded the opportunity to understand the tentative nature of chemistry knowledge and their role in its establishment. Arguably, the students' perceptions of agency increased because climate change "is a problem which calls not only for societal consensus, but also individual action" (Feierabend & Eilks, 2010, p. 178). Ultimately, they found that students responded to the climate change context with high levels of interest and motivation because it called on the students to be innovators in a traditionally content-driven field of study (Feieraben & Eilks, 2010).

It has been shown that the chemistry education literature is calling for relevance and that relevance for general chemistry curriculum could mean context-driven content. In addition, primary context or doing science in practice is a more authentic and just portrayal of science. However, it has also been shown that there are many pragmatic circumstances which limit implementation of these strategies. In addition, some detractors argue that while teaching chemistry in context improves students' affective learning dimensions, affective gains are frequently at the cost of the cognitive. Enter a framework or foregrounding context that problematizes the discipline of chemistry in a way that challenges students to operate in a framework of sustainability where the content *is* the socio-scientific issue to be solved. Green chemistry could potentially alleviate pragmatic constraints of primary contextualization while maintaining academic rigor.

Green Chemistry Contexts

Considered a progressive philosophy of chemistry education, or new epistemology, "green chemistry aims at promoting environmentally benign patterns, a change that is essential for development to be sustainable" (Mammino, 2015, p. 1). Using sustainability as the context, green chemistry (GC) is a set of 12 foregrounding principles that focuses and unifies chemistry through content, rather than through a secondary context. Described in the literature as a best practice, this socio-scientific chemistry philosophy is endorsed by the American Chemical Society (ACS) and the Next Generation Science Standards (NGSS). It has received a lot of attention as of late because of our pressing environmental problems. Here-to-for, the focus has been on the science of green chemistry (e.g., catalysis, alternative solvents, energy); however, its effect on students in higher education, for general chemistry in particular, is not clear. Green chemistry claims to produce positive gains in both student achievement and motivation (Karpudewan, Ismail, & Roth, 2011), as well as facilitating students' personal development (DeJong & Talanquer, 2015; Sjostrom, Rauch, & Eilks, 2015; Taber, 2015).

In the early nineties, green chemistry practices had a decidedly pragmatic and economic focus, in that public policy demanded expensive remediation for waste and damages which could have been prevented by design (Beach, Cui & Anastas, 2009). Since then, the 12 Principles of Green Chemistry have evolved into a design imperative by delivering outputs which reinforce components of the system from which they are derived (Beach et al., 2009). Consequently, green chemical practices become intrinsically and extrinsically sustainable.

At the design level, chemistry can be understood as the root cause for nearly every environmental problem in existence (Feirarbend & Eilks, 2010). Rather than focusing on testing and remediation of environmental problems (i.e., environmental chemistry), the focus of green chemistry is on prevention of environmental problems and chemical disasters starting at the molecular level (Woodhouse & Breyman, 2004). Also known as clean chemistry, environmentally benign chemistry, sustainable chemistry, and atom-economy (Wardencki, Curylo, & Namiesnik, 2004, p. 389), green chemistry can be considered a category under the more global term of 'sustainable development' (Burmeister, Rauch & Eilks, 2011).

Education for Sustainable Development and Green Chemistry

Although they share a similar ethos, 'sustainable development' and 'education for sustainable development' are two different constructs. Sustainable development is defined as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN, 1987). The concept of sustainable development is used by policy makers at the local and global levels to inform and enforce laws (Burmeister, Rauch & Eilks, 2012). Education for Sustainable Development (ESD) emerged from the United Nations Conference on Environment and Development (UNCED) in 1992. Here, UNCED delivered Agenda 21 which defined the central purpose of ESD: "to prepare the younger generation to become responsible citizens in the future" (Burmeister, Rauch & Eilks, 2012). In addition to educating students *about* sustainable development, ESD requires a contextual and pedagogical approach in which students are educated in skills *for* sustainable development, (Burmeister & Eilks, 2013). Although the initial intent of the 12 Principles of GC were industrial in nature, they have been shown to effectively operationalize the goals of ESD through chemistry education (Andraos & Dicks, 2011; Braun, et al., 2006; Burmeister, Rauch, & Eilks, 2012; Juntunen & Aksela, 2014; Karpudewan, Ismail, & Roth, 2011; Klingshirn & Spessard, 2009; Manchanayakage, 2013).

12 Principles of Green Chemistry and Design

The 12 Principles of Green Chemistry were first introduced by Anastas and Warner (1998) in *Green Chemistry: Theory and Practice.* Their book explains the design, development and evaluation of green chemistry practices as they relate to using chemical compounds and catalysts, synthesizing compounds, and novel technologies and processes. The principles were designed to be used in chemistry and chemical engineering as a way to evaluate practices through the lens of environmental sustainability. Essentially, their guiding principles ask that chemists mimic efficient design processes found in nature: "because animals, plants and microbes are the consummate engineers. They have found out what works, what fits in and wat lasts here on earth. After 3.8 billion years of R & D, failures are a fossil, and what surrounds us is the secret to survival" (Janine Benyus, 1997, p. 3, as cited in Cortese, 2003). To use a rather simplistic example, mollusks produce their shells under optimum conditions of ambient temperatures and pressures. Mollusk shells are calcareous exoskeletons produced from calcite and aragonite found in sea water (Encyclopedia of Life, 2016). When the mollusk expires, its shell dissolves and becomes feedstock for another mollusk. Green Chemistry asks that chemists design processes to produce compounds using these same ambient conditions and efficient processes rather than syntheses which require high heat, pressure, and non-renewable feedstock. It is a philosophy of professional practice which "seeks to redesign the materials that make up the basis of our society and our economy-including the materials that generate, store, and transport our energy in ways that are benign for humans and the environment and possess[es] intrinsic sustainability" (Beach, Cui, & Anastas, 2009). Intrinsic sustainability is a systems approach to the practice of chemistry where products and processes are designed for intentional benefits, not just the circumvention of unintended consequences.

To illustrate, Woodhouse & Breyman (2004) provide an exaggerated scenario of traditional chemistry industry practices versus the *12 Principles of Green Chemistry in action* (p. 2-3).

Traditional Chemistry Start with a petroleum-based feedstock:	Green Chemistry Start with a petroleum-based feedstock:
Dissolve it;	*Design each new molecule so as to accelerate both excretion from living organisms and biodegradation in ecosystems;*
add a reagent;	*create the chemical from a carbohydrate (sugar/starch/cellulose) or oleic (oil/fatty) feedstock;*
react the compounds to produce intermediate chemicals;	*and rely on a biological catalyst;*
put these through a long series of additional reactions	*in a small-scale process*
to yield megaton quantities	*that uses no solvents or benign ones*
of potentially dangerous final products;	*and requires only a few small steps,*
release these into the ecosystem and human environments without knowledge of long-term effects,	*creating little or no hazardous waste as by-products;*

without going through gradual scale-up to learn from experience; and	*to yield small quantities of the new chemical for exhaustive toxicology and other testing,*
in the process create millions of tons of hazardous wastes as by-products.	*followed by very gradual scale-up and learning by doing.*
Process threatens the health and well-being of population.	*Process generates new knowledge for future design efficiency.*

Table 1. Traditional chemistry versus GC practices. Adapted from "Green Chemistry as a Social Movement?" by Woodhouse & Breyman, 2004, *Science, Technology, & Human Values*, XX, 1-24.

As social movements go, green chemistry has actually made its way to the mainstream educational literature relatively quickly. One of the earliest courses, *Introduction to Green Chemistry*, was offered at Carnegie Mellon University in 1992. Since then, many universities and colleges have followed suit adopting the green chemistry philosophy by embedding GC concepts into existing curriculum (Manchanayakage, 2013), offering specialized courses and graduate and undergraduate degrees in GC (Braun et al., 2006), or by implementing GC modules into existing chemistry courses (Klinshirn & Spessard, 2009). In some cases, this philosophical shift in chemistry education is in reaction to industry needs for green sustainable practices in manufacturing and chemical engineering (Beach, Cui, & Anastas, 2009). In others, it is a social movement created and sustained through a unifying commitment to sustainable development (Woodhouse & Breyman, 2004).

From the practical side, GC has been shown to be cost-effective, in that it minimizes costs related to laboratory supplies, safety equipment, and hazardous waste disposal. In my own practice, upwards of nearly $10,000 per year is spent on chemical supplies, safety equipment, and hazardous waste disposal. Many of the materials used in green chemistry laboratories are every-day chemicals which can be found in the home. Familiarity with these everyday materials is thought to reduce students' laboratory anxiety (Kingshirn & Spessard, 2009), and contribute to transformative experiences (Karpudewan, Roth & Ismail, 2015), which have been linked to increased conceptual understanding and motivation (Pugh et al, 2010 as cited in Karpudewan et al., 2015). Unlike many other educational programs, there is nothing to buy with the 'buy in', except an ethos- in fact green chemistry laboratories designed to replace traditional laboratories can be accessed through a number of free online sources (Andraos & Dicks, 2012). Depending on the level of integration, adding a new course listing is optional. Even though the environmental benefits verge on being self-evident, there has been resistance to practice green chemistry in both industry and education.

In general, resistance to green chemistry in higher education stems from a number of practical and philosophical sources. Besides the usual 'inertia towards change' and the time it takes to develop new labs, people are hesitant to implement GC because they believe it to be an all-or-nothing effort which can be amotivating (Pelletier, Dion, Tuson, & Green-Deemers, 1999); or, they see it as a less rigorous form of 'hippy chemistry', which has caused it to be further criticized for not teaching students to handle dangerous chemicals (Klingshirn & Spessard, 2009). It has already been shown that most students enrolled in a general chemistry course are not chemistry majors, to wit Klinshirn & Spessard (2009) examined successful case studies of GC implementation into the lecture and laboratory sections of first-year chemistry courses. They found that even small-scale GC integrations through labs and modules were more effective than traditional methods at preparing first-year students for later coursework in chemistry; concurrently, it was found to be more attractive to students normally averse to the subject. To the last barrier, Klingshirn & Spessard (2009) found that students going on to careers in chemistry had plenty of later coursework in which to practice the handling of dangerous chemicals, as well as the added GC background to investigate safer alternatives (Klinshirn & Spessard, 2009).

Burmeister, Eilks, and Rauch (2012) provide basic models for teaching chemistry in the context of sustainability for intermediate and advanced levels. Model 1 in their treatment refers to lab applications, Model 2 addresses the building of content, and Model 3 focuses on problematizing current socio-scientific issues. Particular to this study, Model 1 involves the adoption of GC principles to lab work. It focuses on transforming traditional chemistry experiments into GC practices. Although it is not the most comprehensive of the three models, it is a convenient place for instructors to begin when incorporating the GC principles into their practice (Burmeister, Eilks, & Rauch, 2012; Klinshirn & Spessard, 2009).

Green Chemistry and Perceptions of Agency

Agency surrounding environmental issues usually refers to proxy-agents, or ‘technoscientific solutions’ not people (Hufnagel et al., 2017). Generally speaking, science is seen by many as a proxy-agent, responsible for both our environmental problems and their solutions (Bandura, 2006; Hufnagel et al., 2017; Rudolph, 2014). Emerging from Bandura’s (1977) generative work in social cognitive theory, agency is defined as the power individuals possess to make things happen in their lives (Bandura, 2006). People with a higher sense of agency interpret the outcomes of their own experiences, and they act on them; they do so by changing either themselves or their surroundings to adapt to the new circumstances, which in turn changes their future experiences (Pajares, 2002). If a problem is seen as insurmountable, it is demotivating, as Bandura (2001) notes, "human well-being and attainments require an optimistic and resilient sense of agency" and continues that, "unless people believe they can produce desired effects by their actions they have little incentive to act or to preserve in the face of difficulties" (Bandura, 2001, p. 5). In a general chemistry course designed to embody the grassroots mindset of 'act locally, think globally,' agency is embedded in the context. In short, by doing green chemistry *in* practice- foregrounding the content of chemistry as a problem- students are by default agents participating in a social movement (Woodhouse & Breyman, 2004).

Karpudewan, Roth, and Ismail (2015) investigated the effects of a green chemistry curriculum on students' understanding of chemistry concepts and students' motivation to study chemistry. Karpudewan et al. (2015) contend that green chemistry positively influences motivation because it "embeds task value belief as the content emphasizes [on] the personal importance in thinking about solutions for current and future real-world issues; students enjoy learning chemistry concepts when it allows them to focus on real world issues" (Karpudewan et al., 2015, p. 3). For their study, the authors used a quasi-experimental design where the same six laboratory exercises were used for the experimental group and the control group. The experimental group used a green procedure for the experiment and the control used a conventional experimental procedure organized around the same concepts. Qualitatively, they conducted 20, one-hour interviews with a randomly selected sample to assess the students' motivation towards learning chemistry. The researchers conducted the interviews "to assess the degree to which students' motivation changed within the experimental group in the course of experiencing green chemistry" (Karpudewan et al., 2015, p.6). Interviews were taped, transcribed and analyzed using coding, constant comparison, analytic induction, and description. Data were coded according to self-efficacy belief (low, high), task value belief (low, high), goal orientation (mastery vs. performance), and affect orientation (anxiety, interest). Additionally, a pre-treatment and post- treatment Chemistry Achievement Test (CAT) instrument was constructed using Bloom's taxonomy which covered a range of questions from rote memorization to conceptual understanding of concepts. The pre-test was used as a covariate in ANCOVA design "to control for variance deriving from correlations between achievement and prior knowledge" (Karpudewan et al., 2015, p. 7). Findings revealed very strong evidence for positive gains in the experimental group over the null hypothesis of no difference. Results of the study also showed a higher level of motivation in the experimental group and "those students who started with low self-efficacy, task value belief, goal orientation, and affect orientation (65%, 81%, 50%, and 75% respectively) experienced change to high values on these parameters" (Karpudewan et al., 2015, p. 8). The limitations of the study however are noteworthy: the sample consisted of two classes taught by two different teachers in different schools, therefore threats to internal validity from selection maturation could not be excluded (Karpudewan et al., 2015, p. 14). For future studies, the authors suggest that it would be important to know why and how the students exposed to the green chemistry experimental group showed positive gains in motivation; put another way -were the students empowered as participating agents by learning chemistry content *in practice* versus being trained *as practice*? Or did the students find the everyday chemicals used in the lab work more personally relevant?

In an earlier study, Karpudewan, Ismail, and Roth (2012) found a difference in self-efficacy between pre-service teachers engaged in pro-social green chemistry experiments and those engaged in traditional experiments. The students' intrinsic motivation for pro-environmental behavior increased in the experimental group because they felt empowered by the local approach to a global problem. They found through qualitative interview data that positive changes were due to 'personal satisfaction' felt by the participants as they engaged in pro-environmental behavior (Karpudewan, Ismail, & Roth, 2012). Others might argue that self-efficacy was enhanced because GC mediated the divide between students and society (Gutierrez & Vossoughi, 2010; van Aalsvoort, 2004); by fundamentally changing the practice, it changed the way the students thought about the practice, which changed the whole experience.

In summary, green chemistry is a progressive philosophy of education which unifies the content of chemistry through the collective purpose of sustainability. Green chemistry education is a primary context by which students are recognized as practicing agents in that purpose. It has been shown that a green chemistry context produces positive changes in student motivation by increasing performance indicators such as self-efficacy. Very few studies have been published on the educational impacts of a green chemistry context. Studies that have been published tend to focus on performance indicators such as self-efficacy. However, it has been found that learning for mastery more closely relates to the way motivation is framed in this study, as agentive engagement with content. Further, perceptions of relevance are difficult to measure using performance indicators. Therefore, I chose to use the motivational construct of transformative experience to understand if students found the green chemistry context personally relevant through student engagement with the content.

Transformative Experience

Transformative experience (TE) is an educational theory which is based on Dewey's (1934) understandings about the qualities of an ideal educative experience. Dewey argues that to be educative, learning experiences should be designed to promote transformational learning. A design for transformational learning means that learning should be continuous (i.e., relevant inside and outside of class), present yet expansive (i.e., meaningful), and motivational, a moving force which instigates the desire and purpose for future experiences (Dewey, 1938). Essentially, transformational learning occurs if the individual undergoes a 'personal paradigm shift' by which they are fundamentally changed by the learning; and that the learning forever changes the way in which that individual interacts with the world (Dewey, 1938; Friere, 1970; Mezirow, 1996; Paul, 2015; Wong, 2006). Attenuating this grand ideal to practice, Heddy & Pugh (2015) propose that facilitating transformative experience is an operational way to promote transformational learning in that the aggregate quality of smaller shifts in perspectives may lead to grander learning outcomes (Heddy & Pugh, 2015; Heddy et al., 2016).

Transformative Experience in Science

Distinct from the cognitive, rational theories of transformational learning theory (e.g. Mezirow, 1996), transformative experience studies posit that learning has aesthetic, pathic, and agential qualities which are inseparable from the learning experience. Researchers seek to understand how these dimensions of learning impact experiences in science (Pugh, 2011, as cited in Roth & Jornet, 2014; Roth & Jornet, 2014; Wong, 2007).

To illustrate, Roth and Jornet (2014) report on their provocative inquest into the phenomenological meaning of 'experience' in education. Through the formative works of Dewey and Vygotsky, Roth and Jornet (2014) attempt to frame a theory for the *category of experience* in light of current literature on transformative experience. For their proposed theory, experience is not thought of in colloquial terms "as referring to participation in events or activities and, in the process, having certain feelings" (Roth & Jornet, 2014, p. 2, emphasis in original). Rather, it is defined through the Deweyan ideal of the continuity of experience: an expansive education with temporal dimensions, where "experience is a *category* of thinking, a *minimal unit of analysis* that includes people (their intellectual, affective, and practical characteristics), their material and social environment, their transactional relations (mutual effects on each other), and affect" (Roth & Jornet, 2014, p. 2). Therefore, the *category of experience* they propose cannot be fully understood until the experience itself has ended. They claim that distinction is frequently made between experience and learning, where the former is said to precede or affect the latter" (Roth & Jornet, 2014). While it is agreed that experience has an impact on learning, there is no well- defined 'theory of experience', therefore it remains unclear how learning impacts experience (Roth & Jornet, 2014).

The episode is a recognizably frustrating event between student and teacher in a typical constructivist inquiry lab activity in which the students were tasked with designing a paper lantern. Their case study includes qualitative observation and interview data that were collected as the following event unfolded in a typical 11th grade physics classroom in urban Australia. The teacher initially invited the students to "Design and make a [paper] lantern powered by a single tea-light that takes the shortest time (from lighting the candle) to float up a vertical height of 2.5 m. Investigate the influence of the relevant parameters" (Roth & Jornet, 2014, p. 5). The report and the lantern were to be the only assessment in a ten-week term. Into the second week, the teacher was directed by the head of the department to change the parameters of the assignment to make it ‘easier’ by using hair dryers instead of candles. The study focuses on one student who had been working on designing waxes for the experiment and resisted the change, “what for the teacher was anticipated as a simplification, it turned out to be a disconnect for the student” (Roth & Jornet, 2014, p. 10) and the student “turned off during this lesson and lost interest for the extended experimental investigation for the remainder of the term” (Roth & Jornet, 2014, p. 9). Needless to say, this unintended consequence had a lasting impact on both the teacher and the student.

Details of the narrative aside, they found that it met the category of *an experience* because it had a ‘lasting impact’ on the ways both the student and the teacher would engage with the discipline later. In this case, the transformative experience was detrimental, and Dewey argues that “any experience is mis-educative that has the effect of arresting or distorting the growth of further experience” (Dewey, 1938, p. 25). Certainly, these consequences were not intended by the teacher or the student; however, the experience as a whole will belie their negative perceptions in the future. In this case, the learning was mis-educative because the student chose to dis-engage from learning. Therefore, this is not considered a transformative experience in the educative sense; but can be classified as *an* experience. Roth & Jornet (2014) demonstrate with their analyses that it was the pathic and agential dimensions *during* the experience that counted in the future and acted to ‘tinge’ the perspectives of the student, as well as the teacher, with negative affect about future experiences (Roth & Jornet, 2014). To be sure, experiences are not always transformative in the educative sense, and they are contingent to social and societal variables outside of the experience itself (Paul, 2014).

Elements of Transformative Experience: Increasing Motivation through Engagement

As a motivational construct developed from within the purview of science education (Pugh, Bergstrom, & Spencer, 2017), transformative experience is identified by three key elements: motivated use of concept (MU), expansion of perception (EP), and experiential value (EV), all of which relate to engagement with concepts ranging from inside to outside of class (Pugh, 2011). As a holistic engagement construct, all three elements must be present to constitute a transformative experience, although they need not be present in equal measures (Pugh, Bergstrom, & Spencer, 2017). *Motivated use* is defined as the behavioral component and refers to the student using or discussing concepts outside of class, even when he or she is not required to do so (Pugh et al., 2017). For instance, if after learning about adaptation in class, a student visits a zoo and thinks about the length of a giraffe's neck in relation to principles of adaptation, this would be considered an example of motivated use (Heddy & Sinatra, 2013). *Expansion of perception* is defined as the cognitive dimension where students are thinking about theoretical concepts in relation to everyday observations (Pugh et al., 2017). If the student at the zoo recognizes the length of the giraffe's neck in relationship to its primary food source, the acacia tree, this would be an example of expansion of perception (Heddy & Sinatra, 2013). *Experiential value* is the affective component which is demonstrated by the student, "who comes to appreciate the material for its ability to transform his or her experience of the world" (Heddy & Sinatra, 2013, p. 725). This could mean that the student not only recognizes the relationship of the giraffe to the acacia tree, but that she or he also understands the connection of that ecological relationship to his or her own life (Heddy & Sinatra, 2013). In essence, transformative experience is a holistic form of engagement which leads to a change in the ways in which a student interacts with concepts outside of class (Pugh et al., 2010); or more specifically, it leads to “enaction in the learner, not simply awareness” (Caruana, Woodrow, & Perez, 2015, p. 27). Thereby, students learning for TE may demonstrate observable evidence that engagement with the concept changed their thinking, behavior, or emotions with respect to phenomena in class, or in their lives outside of class. Similar to other theories of how engagement facilitates transfer, transformative experience has been shown to increase the ability of students to apply content learning to novel contexts. Different from the traditional idea of transfer, transformative experience incorporates feeling, value, and action (Pugh et al., 2009).

Transformative Experience and Personal Relevance

Transformative experience is thought to influence important student outcomes such as engagement and transfer (Caruana, Woodrow, & Perez, 2015; Girod et al., 2010; Heddy et al., 2016; Pugh et al., 2009; Pugh et al., 2016), as well as motivation and conceptual change (Heddy et al., 2016; Pugh et al., 2009), and higher interest and efficacy beliefs (Girod, Twyman & Wojcikiewicz, 2010). However, it should be noted that much of the research dedicated to TE postulates that “transformative experience is a valued learning outcome in its own right” (Pugh et al., 2009, p. 6). To this point, it is suggested that educators ask, “Do the concepts make any difference in the students’ every day, out-of-school lives?” rather than simply, “Do students understand the concepts correctly?” (Pugh & Girod, 2006, p. 10). From this aesthetic, rather than purely constructivist perspective, “science has the potential to enrich everyday life, vitalize experience, and provide us with aesthetic satisfaction” (Pugh & Girod, 2006). Put another way, concepts that students are asked to learn in science should be personally relevant and meaningful to the student so that the student wants to engage with the concepts outside of class.

To clarify what this means, Pugh & Girod (2006) apply Dewey's ideas of art and aesthetics to science education. Citing the work and musings of great scientists (e.g., Feynman), they distill the benefits of appreciating aesthetic qualities of science such as imagination and creativity; which can be powerful drivers of motivation and desire to learn science (Girod et al., 2010; Pugh & Girod, 2006). In spite of the available evidence to the contrary, quality science education is still thought of in terms of standardization and the cognitive rational mindset which focuses on 'the acquisition of the language of science' (Girod, Twyman, & Wojcikiewicz, 2010; Pugh & Girod, 2006). By this, they do not suggest that established concepts are not important, rather, they suggest methods of crafting established concepts into 'living ideas' which require design and action (Pugh & Girod, 2006). In other words, when students are invited to critically reflect and act on content, their personal perspectives are likewise evaluated in response, which may result in a shift of perspective (Caruana, Woodrow, & Perez, 2015).

To explain, Pugh (2002) conducted a small exploratory study designed to gauge the effectiveness of two different instructional elements thought to contribute to students' transformative experiences in science. The author used a mixed-method approach to understand how "engagement with concepts fosters enriched experiences" (Pugh, 2002, p. 1101). In particular, the study explores two instructional elements of teaching purported to facilitate students' transformative experiences: the artistic crafting of content and an apprenticeship approach. Artistic crafting of content means that the teacher should aspire to reanimate concepts which have become common and standardized in the content, "to craft ordinary (and uninspiring) concepts into powerful ideas that have the potential to instigate action, transform perception, and expand value" (Pugh, 2002, p. 1105). The goal of the teacher in the apprenticeship approach is to engage the students in the class in such a way that their experience is carried to their world outside of class by explaining personal relevance, “how a concept functions as a true idea for him or her by modeling everyday use of the concept” and also by “modeling the excitement or satisfaction that comes from doing so” (Pugh, 2002, p. 1106). In order that the student sees how the concepts influence the teacher.

The effectiveness of these two elements were explored by comparing the TE classroom to another classroom using the same content, but via case-study method. Students were assessed based on the degree to which there was evidence that they had transformative experiences. Pugh (2002) devised two research questions to understand the effectiveness of the two instructional elements: How effective are the two instructional elements (taken together) at fostering transformative experience? And, are these instructional elements more effective than the case-study method of instruction? The experimental group and the control group consisted of two zoology classes which were normally taught by the same progressive veteran teacher at a large suburban high school in the Midwest. The author of the study taught concepts of evolution and adaptation to both the control group and the experimental group during the 2.5-week intervention. The population in the experimental group consisted of 17 students (53% female and 6% minority) and in the control group there were 22 (45% female and 5% minority). Similarities and differences of both progressive pedagogical approaches are described in detail and include: discussions, lab activities, group projects, and intentional modeling and scaffolding of content. Control variables included situational interest and level of conceptual understanding “to help determine the validity of the case-based class as a comparison condition by indicating whether it represents ‘good’ instruction in that students learned the content and enjoyed the class” (Pugh, 2002, p. 1112). Both of which are thought to be valuable outcomes of student engagement with the concepts.

Initial data collection also utilized four open response questions designed to elicit student responses with respect to the three qualities of TE: active use of concept, expansion of perception, and experiential value. In addition, the author gave students an assignment which sought to assess students' active use of the concept of adaptation. A similar post intervention survey was also administered to assess students' interest in the concepts and their perception of how worthwhile learning the concepts was to them. The post intervention survey also contained nine open-response questions which asked for examples of concepts, how and if their perception of animals had changed, it their interest had changed, and asked students to comment on why and if they found the concepts to be worthwhile or interesting. Finally, the students took an 'assessment of understanding' about the concepts. A follow-up assessment was given a month later containing two open response questions and four survey items to check for student understanding and everyday use. Additional data were generated from video recordings of the classes and post-intervention interviews.

Results overall showed that TE was higher for the experimental group that was taught intentionally for TE, "in the context of this study, an artistic crafting of content and modeling and scaffolding of perception and value were relatively effective instructional elements for fostering transformative experiences" (Pugh, 2002, p. 1130). The data analysis showed no statistical differences when including measures of situational interest or conceptual understanding. However, it was noted that of the three outcomes of TE that were assessed, the effect on expansion of value was not clear (Pugh, 2002). Notably, both classes scored equally well on the assessment of understanding at the conclusion of the intervention, but the experimental group scored higher on the follow-up assessment months later, inferring that the group taught purposefully for TE demonstrated a higher degree of conceptual change (Pugh, 2002). For this study, it would be important to understand other factors related to the instructional elements that Pugh (2002) proposes. Was his teaching more animated and excited in the experimental group? Or, did he provide examples that were more relevant to the students' lives?

In an effort to define the instructional elements of teaching for TE, Pugh & Girod (2007) outline what these instructional elements look like. The TTES model provides three methods for teaching for transformative experience in science: Framing content in terms of its experiential value, modeling transformative experiences, and scaffolding the re-seeing of content (Pugh & Girod, 2007, as cited in Heddy & Sinatra, 2013). Heddy and Sinatra (2013) explored the effectiveness of the instructional elements of TE further refined and outlined by Pugh & Girod (2007) in their teaching for transformative experiences in science (TTES) model. The authors hypothesize that students who engage in transformative experience evidence positive emotions "which in turn could contribute to conceptual change" (Heddy & Sinatra, 2013, p. 726). A total of 55 undergraduates enrolled in educational psychology course at a large southwestern university were taught concepts of evolution using the TTES model and were compared with students who were taught using another progressive method of instruction and discussion. It is believed that concepts which require an 'emergent systems' approach like natural selection and climate change do not lend themselves to students relating content to everyday experiences because they require non-demonstrative forms of evidence rather than 'causal accounts of direct systems' (Heddy & Sinatra, 2013; Rudolph, 2014b). Using the Transformative Experience Questionnaire (TEQ) developed by Pugh et al. (2010), and 3 open-ended questions which referred to engagement outside of class (expansion of perception and recognition of value), the study explored the TTES model in relation to student engagement, conceptual change, and affect. Results indicated that teaching with the TTES model facilitated both learning and enjoyment of the content. The authors suggest that the TTES model of instruction may be especially useful in these cases, because it mediates the science content by framing it in a way that influences students' everyday experiences (Heddy & Sinatra, 2013). Similarly, researchers have found that targeting instruction specifically for TE has been shown to positively influences students' affective domains because it helps them understand the relevance of the concepts to their own lives (Caruana, Woodrow, & Perez, 2015; Heddy & Sinatra, 2013), which may facilitate a re-engagement with the concepts outside of class (Heddy et al., 2016).

Facilitating Transformative Experience through Green Chemistry

While it is understood that educators cannot directly cause transformative experiences to occur in their students (Pugh et al., 2009; Wong, 2007), some researchers suggest that transformative experiences can be stimulated by influencing *how* students engage with concepts (Girod, Twyman, & Wojcikiewicz, 2010; Wong 2007). It has been shown that the purposeful teaching of content using instructional elements of transformative experience (i.e., TTES) can facilitate students' transformative experiences (Heddy & Sinatra, 2013; Heddy et al., 2016; Pugh, 2002, 2011). As stated earlier, it is thought that high misconception topics like evolution and climate change lend themselves more readily to evidence of transformative experience, because growth is more readily observed and measured (Pugh, Linnenbrink-Garcia, Koskey, Stewart, & Manzey, 2009). While chemistry as a discipline is not considered a high-misconception topic, TE's can also be facilitated by problematizing standardized content in a way that encourages students to engage with them as possibilities that need to be acted upon and tried out (Pugh, 2002). Green chemistry may facilitate transformative experiences in chemistry because the standardized chemistry content is 'reanimated' (or problematized) in a way that encourages students to engage with the concepts as participating agents in the making of science for the fundamental purpose of sustainability. Further, this perspective places the student in the role of *autonomous* agent in the decision-making process because there are ‘shades of green’ when evaluating green laboratory procedures (Andraos & Dicks, 2012). Similar to improvement science, GC is an ‘iterative process’ and there is no assumption that one particular approach is the best (Andraos & Dicks, 2012; Sjostrom & Talanquer, 2014). Put another way, GC makes transparent the fact that the work is never *done*.

Wong (2007) argues that anticipation or an “imaginative sense of possibility” is a non-cognitive source of motivation that is often neglected by the constructivist paradigm and “is heightened as students engage with worthwhile ideas” (Wong, 2007, p. 211). In fact, it has been found that an ‘imaginative sense of possibility’ is a powerful and often neglected component of student engagement (Wong, 2007). Notably, the word experience itself has a linguist etymology which relates to “travel, traversal, peril, risk, and change” (Roth & Jornet, 2014, p. 14). There is an element of risk associated with being open to an experience. That is to say, students do not have to relinquish their agency or autonomy, quite the opposite. They do have to trust that what they are learning is valuable and compelling enough to ‘be receptive to outside influence’ and agentively engage with the concepts for a transformative experience to occur (Wong, 2007). Otherwise characterized as ‘surrender’, it is an element of TE beyond the direct control of the educator, because “it requires an opening up to and a submersion in the possibility of the experience” (Pugh, 2002, p. 1134). Essentially, the quality of the learning experience depends on the individual buying in to the socially authored objective learning conditions, because the individual becomes a part of those conditions (Dewey, 1938; Wong, 2007). To rephrase it, ideas must be embraced as if they were true, if even for a while (Wong, 2007). And, as stated earlier, students are more open to transformative experiences when they are asked to learn things that they believe are meaningful and worthwhile (Wong, 2007). This optimistic sense of possibility is what supported my own TE with respect to my discipline. Learning about the principles of GC and understanding the consequences of not improving my practice provided me with a sense of purpose and motivation to be a better teacher. I am no longer teaching for myself, or my students, I am teaching for a worthwhile purpose that far outreaches my grasp in the classroom. It was the optimistic sense of possibility that caused my TE with respect to teaching chemistry that I felt would also benefit my students.

To summarize, experiences are transformative experiences in the educative sense if they contribute to enaction in the learner. TE's are characterized by students' agentive engagement with the concepts which are observable behaviors demonstrated by expansion of perception, experiential value, and motivated use. And, it has been found that students are more open to transformative experiences when they are asked to learn things that are meaningful and worthwhile. If the content of chemistry is seen as personally relevant and globally valuable (i.e. green chemistry), students may be more open to transformative experiences in chemistry. Moreover, courses challenging the commodified nature of chemistry may make it easier for TE's to occur through student perceptions of personal or collective agency, because the context is imbued with the perception that we are all in this together.

Improvement Research

The fact that science education has been in a ‘constant state of reform’ for hundreds of years is an indicator that warrants a change in how science educators think about educational research (De Boer, 1991). Typically, research in education done to advance a theory or for accountability purposes. On both accounts, performance is measured and under-performance is evaluated (Yeager et al., 2017, draft, p. 3). While this research may be valuable given certain delimiting circumstances, educators are imposed upon to ‘buy’ and ‘buy into’ meritocratic ideas for change that may not work or even be warranted in their local contexts, despite being empirically vetted in a specific context (Bryk et al., 2015; Mintrop, 2016). Commonly, this results in innovation-without-change, because reform ideas are imposed upon, rather than generated from within the system they intend to change (Bryk, et al., 2015; Gilbert, et al., 2004; Mintrop, 2016). It is suspected that many promising ideas in education lack potency in practice because research is often driven by investigating what should work given a generalized theory, rather than what can work in a specified setting (Lazowski & Hulleman, 2016; Rudolph, 2014a). In response, there is a growing cadre of researchers and practitioners seeking to recognize the elephant in the room that is often left unaddressed in educational research: “What should I do now in my classroom based on your research” (Lazowski and Hulleman, 2016, p. 28)? In this section, I explain why improvement research challenges traditional research standards by integrating the work of both theoreticians and practitioners to solve complex problems in education. Then, I explain why methods of practical measurement were chosen for the methodology in this study.

Challenging the Experimental Research Paradigm in Education

Many authors confess that while their findings are important, results from experimentally designed interventions should be understood with caution because of the complexities involved when translating research into practice (Coe, 2002; Lazowski & Hulleman, 2016). In some cases, teachers are not effectively trained to implement interventions with fidelity (e.g., competence), and even more do not have the time and support (e.g., capacity) to collect data and report findings from actual 'contextually bound' classroom settings (Bryk et al., 2015; Lazowski & Hulleman, 2016). Thereby, the variability of results from actual practice in different contexts goes unrecognized and under-published and the theory sits unchallenged, which does not inform further development of the theory. To further muddle the evidence, long instruments which are often designed to measure overlapping constructs may be too specific (or too general) to inform day-to-day-practice (Yeager et al., draft, 2017). And as any educator or researcher understands, the 'empirical phenomena' we are studying "is a knowing participant who can resist, cooperate, or simply not engage in the instruction being observed" which are not faculties possessed by the simplistic systems that the scientific experimental method was developed to describe (Rudolph, 2014b, p. 4).

As a science educator, I understand how difficult it is to control for all of the variables in even the most simplistic systems of study. For example, an experiment designed to compare the heart rates of daphnia exposed to geranium oil (a natural insect repellent) and and N-N-Diethyl-meta-toluamide (DEET) requires a laborious set of experimental protocols to ensure that the design in reproducible in very discreet environmental contexts. Even this relatively simple experimental design is fraught with the potential random (i.e., unpredictable) and systematic (i.e., consistent) errors which can produce data that are only considered evidence if the same results are produced repeatedly by different researchers in different labs. Even though experimental criterions for rigor have glaring limits in a classroom full of multi-celled individuals with varying ages, abilities, identities, and needs, the experimental design continues to be the 'gold standard' for many of the producers, users, and funders of educational research (Rudolph, 2014b). In fact, for science in general, the experimental model actually occupies a 'narrow band' in the field of scientific research and even then, "methods of inquiry are highly contextual, contingent, and emergent over time" (Rudolph, 2014a, p. 3). The unintended consequences of perpetuating this 'narrow band' approach to our work are concerning: Hope may be lost that our research can actually improve practice and empirical evidence will be ignored; or education may be designed to conform to the experimental protocols of the research so that data more accurately informs practice (Rudolph, 2014b). Both of these outcomes are unintended and unacceptable.

Practical Measurement

Simply put, researchers cannot improve at scale what cannot be accurately measured in a local context (Bryk et al., 2013; Mintrop, 2016, Yeager et al., draft, 2017). Indicating that a change is actually an improvement requires forms of practical measurement which are different from generalizable statistics routinely used in education. The focus of practical measurement is on predictive validity within local, rather than global environments first; where the ultimate or goal is to decrease variability in outcomes between different learning environments (Yeager et al., 2017). As more measures are generated in local contexts- changes are made summarily, before the change is practiced to scale (Bryk, Gomez, & Grunow, 2010). That is, rather than placing emphasis on the scientific replicability of the research findings, practical measurement relishes idiosyncratic results which provide for a more nuanced understanding of the observed measures (Bryk et al., draft, 2013; Yeager et al., draft, 2017). Consequently, practical measurement shifts the focus from the ‘gold standard’ of imposition and generalizability, to the particularities of “what works, under what conditions, and for whom” (Gutierrez & Penuel, 2014). This rhizomatic approach calls on practitioners to actively research their ideas for improvement and does not depend solely on scholars to develop solutions to be implemented by practitioners, rather, an idea for improvement exists at this interface of research and practice. Because, “without this kind of idea testing, our theories will not be pushed to grow, and knowledge about how to best structure educational environments will be limited” (Lazowski & Hulleman, 2016). However, the challenges for improvement research in a local context are noteworthy: Empirical evidence used as data is may not be statistically significant with small non-parametric populations, so while issues of psychometric reliability and validity may not apply, this study is conscientious about not only what the data relates, but more importantly, what it does not. Finally, improvement research is a relatively new research paradigm in education and the traditional scientific experimental methodology is still considered the gold standard by many educators and the general public (Rudolph, 2014a, 2014b).

Chapter 3

The purpose of this study was to determine if there was evidence that green chemistry (GC) laboratory experiments facilitated students' transformative experiences (TE) in a first-semester general chemistry course for science majors. Three signature green chemistry experiments replaced traditional labs designed to investigate the same chemical concepts found in the traditional chemistry curriculum. Practical measures included impact data from the Transformative Experiences Questionnaire (TEQ) and guided reflection questions which were coded for elements of TE using a rubric appropriate to the instructional goals. Quantitative data were analyzed using the Wilcoxon signed rank statistic to determine TE effect sizes for each lab and TE effect size across the labs. Subscale effects of expansion of perception (EP), experiential value (EV) and motivated use (MU) for each lab and across the labs are also presented. Process data are also included to provide contextual understanding of the impact data. First, the study context is described, and methods of data management and analysis are explained. Then findings are presented for each individual lab and across the labs.

Methodology: Convergent Parallel Design

A convergent parallel mixed method design was utilized to provide for a more robust and contextualized understanding of the quantitative and qualitative TE data (Creswell & Plano-Clark, 2011). This is a research design in which quantitative and qualitative data are collected in parallel, analyzed separately, and then merged for interpretation. These data were collected and analyzed independently for both survey and written response evidence of TE. Interpretation of data sought to understand if there was evidence that green chemistry laboratories facilitated students' transformative experiences in chemistry. Interpretive mixing of impact and process data did not occur until the end of the study. The different but complementary data sets were merged to understand the extent to which the data complemented or contradicted each other, and to understand how the data differed with respect to each laboratory experiment, and each element of TE. These data were necessary to understand the evidence related to students' transformative experiences in the undergraduate general chemistry course with respect to the research question:

What is the evidence that green chemistry laboratory experiments facilitated transformative experiences for students enrolled in a first-semester general chemistry course?

Study Context and Timeline

This study was conducted during the second half of the Spring 2017 at 'Green University'. The researcher was the instructor of the General Chemistry course and the corresponding laboratory section. Students enrolled in the course made up the population for the study (N=18). Approval to conduct this study was granted by Green University IRB and Duquesne University IRB. The three green chemistry laboratories were implemented as replacement labs for traditional experiments over a six-week period during the second half of the spring semester. Each laboratory experience was designed to last two weeks. A catalogue description of the general chemistry course, and an overview of the three green laboratory experiments follow.

General Chemistry

From the Green University catalogue 2016-2017:

> A treatment of the states of matter and the laws governing chemical and physical changes (including kinetics and equilibria), founded on modern concepts of atomic structure and chemical bonding. First semester. Three hours of lecture/recitation, and one three-hour laboratory period each week. Co-requisite: MAT 108 or a satisfactory score on the Mathematics Placement Examination. This course is intended for science majors. Fall.

This American Chemical Society (ACS) accredited course is offered in both the fall and spring semesters. Students must successfully complete this course with a C minus to continue in the general chemistry course sequence. Both courses in the sequence are required for students majoring in pre-medical, pre-dental, secondary education, chemical management, environmental science, engineering, forensic science or forensic chemistry. Traditional experiments offered in this course include: percent yield of reactions, spectrophotometry, concentration and dilution of solutions, acid-base neutralization titrations, redox-reactions, and solution stoichiometry. The experiments follow traditional pedagogical procedures where directions are provided in the laboratory experiment handout and reviewed by the instructor during the pre-lab session. Usually, there is a discussion of procedures, safety concerns, waste disposal, and expected results which precede the laboratory experiment. Students were required to write up their pre-lab procedures and collect experimental data and observations in a laboratory notebook. Student lab reports are generated using the ACS laboratory report template.

Green Chemistry Laboratories

Three traditional laboratory experiments were replaced with signature green chemistry experiments which were modified by the researcher using previously published green chemistry experiments from Beyond Benign (www.beyondbenign.org). The three green chemistry experiments were reviewed by the chair of the chemistry department and a senior secondary chemistry education major to ensure the academic integrity of the green laboratory experiments. Each lab was foregrounded by the 12 Principles of Green Chemistry. The three laboratory experiments can be found on the Beyond Benign website (www.beyondbenign.com) and are summarized below:

- Essential Oil Extraction Using Supercritical CO_2 - Students explore and compare the percent yields from both a steam distillation and a supercritical fluid extraction of d-limonene from citrus rinds. Both extraction methods are evaluated against the 12 Principles of Green Chemistry.

- Solubility - Students qualitatively and quantitatively describe the relationship between temperature and solubility for gases and solids. This lab uses two forms of magnesium (magnesium chloride and magnesium sulfate) to compare solubility of ionic solids and create a solubility curve. Solubility of gases is demonstrated by a simple demonstration experiment involving carbonated water and temperature differences.

- Synthesis and Analysis of Biodiesel – This experiment demonstrates the use of vegetable oil as an alternative and renewable feedstock. The reaction incorporates NaOH (or KOH) as a catalyst in order to achieve high yield and minimize waste. Students synthesize biodiesel fuel using a transesterification reaction. This reaction incorporates the use of a strong base in a catalyzed nucleophilic addition-elimination reaction at the carbonyl carbon of the triglyceride.

Student Laboratory Work

As part of normative departmental practices, students generated formal laboratory reports following each laboratory experiment. Apart from normative practice, students were asked to include an evaluation of the experiment based on one or more of the 12 Principles of Green Chemistry. For example, in the Essential Oil Extraction, students were asked to compare percent recovery using traditional steam distillation techniques versus using carbon dioxide extraction. They were asked to compare each technique using one or more of the green chemistry principles as they apply to the lab and to industrial scale processes. Figure 1 depicts an example of this evaluation.

Figure, 1.

GC Principle	Traditional solvent extraction	Steam distillation extraction	Supercritical CO_2 extraction
#7 Renewable Feedstocks	The solvents used are petroleum derivatives. Petroleum is a non-renewable resource.	This process utilizes large amounts of water. Although technically water is a renewable resource, on an industrial scale water is taken from rivers and put back into the watershed at temperatures that are not consistent with the	CO2 is a renewable resource

		health of the rivers. Although often this water was recycled.	

Figure, 1. Example of student lab sheet comparing essential oil extraction. Adapted from Extraction of d-limonene[…]student-sheet, retrieved from http://beyondbenign.org, 2010.

Participants

Students consenting to participate in the study were all enrolled in the General Chemistry course and corresponding laboratory section. As noted earlier, students enrolled in this course during the spring semester are typically those who did not meet the math pre-requisites for beginning the general chemistry sequence in the fall, transfer students, or students not passing the course with a C minus in a previous semester. A total of 18 students were enrolled in the spring section of the course. The laboratory section of the course met for three hours each week. All students consented to participate in the study. Consent procedures can be found in the IRB document Appendix, B.

Data Collection Protocols

Data were collected over a six-week period during the implementation phase of the three green laboratory experiments. In line with the practices of the chemistry department, each green laboratory experiment was designed as a two-week laboratory session. Quantitative TE survey data were collected immediately before and immediately after each experiment in the 6-week GC laboratory experience. Qualitative student TE reflection response data were generated following each experiment through written guided reflection questions. Reflections on the laboratory experiments were due one week following the experiments and were separate from students' regular graded laboratory reports. Student survey data and response data were kept in a locked file cabinet and de-identified using a student number when processed for data analysis.

Data Management and Analysis

This study relied on methods of practical measurement to understand the evidence related to students' TE with respect to each laboratory experiment and across the 6-week GC laboratory experience. Statistics were generated to measure relative effect sizes based on survey data. These measures were chosen for course improvement purposes and data were not generated or analyzed to determine generalizable significance. In this section, I describe how data were managed and analyzed using two different scales for the survey and response data. Procedures for reliability and validity of the data are also discussed.

Transformative Experience Questionnaire

The Transformative Experience Questionnaire-Properties of Matter Form (TEQ) developed by Pugh et al. (2009) and validated by Koskey et al. (2016) was used to collect quantitative TE impact data pre/post for each laboratory experiment (see, Appendix C). A total of 6 quantitative TEQ surveys were administered over the course of the six-week green chemistry laboratory sequence. The TEQ was designed to measure a composite TE score for student engagement with science concepts they are learning in class, and the transfer of their learning to some phenomena (e.g., object or process) outside of class (Koskey et al., 2016). Statements regarding behaviors (i.e., talking about, noticing) rather than dispositions (i.e., confidence), are divided into three categories: motivated use (MU), experiential value (EV), and expansion of perception (EP). The TEQ instrument has a total of 27 questions pertaining to the three elements (or domains) of TE: 7 relating to expansion of perception (EP), 9 relating to experiential value (EV), and 11 relating to motivated use (MU).

Following the recommendation of the author of the TEQ, the general TEQ-Properties of Matter form was completed before each two-week lab session and modified to be specific to the content covered in the experiment for the post-lab TEQ measure (Pugh, personal communication, Jan. 19, 2017). For example, item #26 on the general form (pre-Biodiesel Lab 2) reads, "*I'm interested when I hear things about the chemical properties of matter outside of class*" and the post lab TEQ measure reads, *"I'm interested when I hear about thermochemical fuel values outside of class"*. Importantly, students were reminded that 'outside of class' did not refer to homework or other course requirements, as was recommended in the validation study conducted by Koskey et al. (2016). Koskey et al. (2016) used the mixed-method Instrument Development and Construct Validation Process (IDCV) to validate measures in the TEQ-Properties of Matter Form. The interrater reliability of the data was reported to be moderate but indicated statistically significant agreement when coded for answer conformity (Kappa = .478, $p < .001$).

Four Likert-type scale choices were provided to dissuade a neutral choice (Shreiber & Asner-Self, 2011): 1-strongly disagree, 2-disagree, 3-agree, and 4-strongly agree. These TEQ data were transferred from the TEQ survey forms and entered into Excel spreadsheets. Each question was labelled with a student number (1-18), a corresponding lab number (1, 2, or 3), the TEQ question number (1-27), and the response (1, 2, 3, or 4). Data from all three labs were combined into two excel spreadsheets delimited by columns in both a left-to-right and stacked organizational format for analysis. The nominal variables of the pre/post TEQ data were assigned an ordinal value of 0 or 1 respectively. Non-parametric tests were used because no assumption could be made that the data were normally distributed. Further, there was no null hypothesis and due to the small population, my analyses relied on the practical significance of the data with respect to the research question (Schreiber & Asner-Self, 2011). Arguably, the TEQ is a Likert-type survey not a true Likert-scale survey, therefore the data were treated as ordinal rather than continuous which limited the types of statistical analyses that could be performed (Shreiber & Asner-Self, 2011). Because the TEQ was administered pre/post each lab, the data were treated as dependent (i.e., matched pairs), by lab, for all analyses.

Composite TEQ scores for each lab were generated in Excel. These data were then imported into JMP to calculate the Wilcoxon Signed-Rank (WSR) statistic based on matched pairs of the composite mean scores between the pre-lab and post-lab TEQ for each experiment. Data were also imported into the Social Science Statistics (www.socscistatistics.com) WSR calculator for confirmation. The WSR was used because it is a non-parametric alternative to the paired sample t-test and the study population was not assumed to be normally distributed (Shreiber & Asner-Self, 2011). Measured on an ordinal rather than a continuous scale, the WSR statistic was used to compare the mean TEQ scores of student responses using a matched pairs analysis of post-TEQ minus pre-TEQ scores for each question, in each time (t=3). Because there is no familiar scale to compare TEQ scores with, these data were used to understand the relative differences in magnitude of the mean ranks between the post-TEQ and pre-TEQ for each lab.

Further analysis of the data was performed in Excel using the WSR statistic to calculate relative effect sizes (*r*) of each lab according to the formula: $r = Z / \sqrt{(n_x+n_y)}$, where r = effect size and Z = the WSR statistic, and $n_x+n_y = 18+18$ for the number of observations at the two different time points. Effect size is a calculation which measures the relative size of the effect between two groups (Coe, 2002). In this case, the groups were represented by time 1 and time 2 TEQ surveys for three different labs, in the same population of students (N=18). Similar to a meta-analysis, the two groups or times for each lab were considered the control (pre-lab) and treatment (post-lab). Different from a standard Cohen's effect size (*d*) which uses the difference between the means divided by the square root of a pooled standard deviation. Because the TEQ was designed to give a composite score for TE, totals were used from all students by lab, to determine the effect size of TEQ scores by lab. As appropriate, the effect size, *r*, was calculated using the WSR statistic.

Additionally, a fourth group effect size was calculated which used the first mean TEQ composite scores (pre-Lab 1) against the final mean TEQ composite scores (post-Lab 3). Performing a group effect size calculation for all three labs and an overall measure (pre-Lab 1 and post-Lab 3), the data were compared to emphasize the power of the difference, where the difference was quantified between the pre-TEQ and post-TEQ measure for each experiment and overall. Because there is no familiar scale to compare TE measures with, the amount of variation in the group scores was a practical and more meaningful way to contextualize the student differences in TE for each lab experiment (Coe, 2002). For a more operationalized comparison scale, this study uses Cohen's classification of effect size: small = 0.2, medium = 0.5, and large = 0.8 (Cohen, 1988, as cited in Coe, 2002). However, Cohen (1988) and other researchers warn that the effectiveness of any type of intervention "can only be interpreted in relation to other interventions that seek to produce the same effect" (Glass et al., 1981, p. 104, as cited by Coe, 2002). Therefore, the effect size calculations in this study should only be understood for comparison purposes between the labs. The practical importance of calculating the effect sizes for each group by lab produced an estimate of the relative impact of each of the three labs on students' TE. Contextual complexities from student backgrounds and a 'restricted' range of students from one small university limit the generalizability of these findings to a larger population (Coe, 2002; Schreiber & Asner-Self, 2011). Because this study focused on practical rather than generalizable measures, the relative effect sizes can be used for comparison and improvement purposes and are considered educationally significant to the user (Coe, 2002).

Transformative Experience Reflections

Qualitative TE data were generated using guided reflections upon completion of each of the laboratory experiments. Reflection questions were adapted from Girod et al. (2010) and modified for content based on the chemistry concepts the laboratory experiments were designed to cover (see, Appendix D). The first question refers to expansion of perception (EP), the second question refers to experiential value (EV), and the third question refers to motivated use (MU). Because these reflection questions were adapted from interview questions, they were parsed out to elicit sufficiently thorough answers for parallel or duplicative questions. In other words, designed in a way that minimized 'yes' or 'no' type responses (Merriam, 2001).

1. *Did you learn anything during the course of this experiment that made you think differently about the world or see things differently? If so, explain why these ideas made you see the world differently. If not, why didn't learning make you see the world differently?*

2. *Was learning about the ideas in this experiment interesting or valuable? In what ways? Was it more interesting or valuable than other things you learn in chemistry? If so, what was different about it? If not, why not?*
3. *Did you do anything differently as a result of this new learning? Did you tell anybody else about what you learned during this experiment? Did you try to learn more about any of the ideas on your own? Did you look for examples of what you leaned outside of the lab? Tell me why or why not.*

Student responses to the reflection questions were collected one week following the completion of each green laboratory experiment. Reflection responses for each lab were then transcribed into a Word document organized by student identification number and laboratory. Qualitative TE data were coded (Merriam, 2001) according to the *a priori* themes: Expansion of perception (EP), experiential value (EV), and motivated use (MU). The reflection responses from each of the three lab experiments were then coded and scored using a rubric ranging from a score of zero (i.e., no response or no evidence of EP, EV, or MU), to a score of 3 (i.e., student provided strong evidence of EP, EV, or MU). Reducing the qualitative responses to a numerical rubric is a strategy employed in qualitative research to illuminate the differences between participant responses to questions that the *a priori* codes were designed to explore (Cresswell & Plano-Clark, 2011). In this case, the reflection questions sought to understand evidence related to EP, EV, and MU. Therefore, these data were treated as frequency counts to reflect the percentage of student responses receiving scores of 0, 1, 2, 3 for each element of TE in each lab.

This scoring system was adapted from recent research conducted by Pugh et al. (2017) as shown in Table 2. The interrater reliability for the rubric was reported by Pugh et al. (2017)

using the intra-class correlation (ICC) which assesses the "raters' composite characteristic scores prior to discussion and resolution" (Halgren, 2012 as cited in Pugh et al., 2017). Scores from the ICC determined interrater reliability to be relatively high: MU (.94), EP (.95), and EV (.94). The reliability of the rubric for this study was also established by interrater agreement. As the rubric used in this study was designed to be used by classroom science teachers to score interview or reflection responses to improve instruction for TE, two college science teachers were recruited to assess all of the de-identified reflection questions using the rubric. Percent agreement with the PI scores was found to be 86%. Given this high level of agreement, PI scores were used for all analyses. Student scores based on the rubric were entered into Excel to generate percentages based on the frequency of scores for the elements of TE and composite scores for the elements of TE (EP, EV, and MU) for all labs. These scores were then illustrated in a chart to examine any differences found between the labs and the elements of TE.

Table, 2.

Reflection Coding Rubric for Elements of TE.

	Elements of Transformative Experience		
Score	**Expansion of Perception**	**Experiential Value**	**Motivated Use**
0	Responded that the lab experience did not change their perceptions about the world.	Responded that the lab experience was not interesting or of any value.	Responded that the lab experience did not influence any behaviors outside of lab.
1	Responded that the lab changed their perceptions about the world but did not provide any examples or explain.	Responded that the lab was interesting and had value but did not provide provide examples or explain why they found it interesting or valuable.	Responded that the lab influenced one or more behaviors but did not provide examples or explain.
2	Responded that the lab changed their perception about the world and provided a detailed example or explanation.	Responded that the lab was interesting and had value and provided an example or explanation.	Responded that the lab influenced one or more behaviors and provided an example or explanation.
3	Provided a detailed example or explanation of how the lab changed their perception of the world and related it to their everyday experience.	Provided a detailed example and explanation of why the lab was interesting or valuable and related it to their everyday experience.	Provided a detailed explanation and example of how the lab influenced one or more behaviors outside of class.

Adapted from Pugh et al. (2017). Profiles of Transformative Engagement: Identification, Description, and Relation to Learning and Instruction.

Table 2 provided an *a priori* coding rubric for the (n=158) written TE reflection responses. Using student #11 and Lab 1 as an exemplar of the coding rubric, this student scored a 2 for the first question referring to EP. The student responded that their perception had changed and provided an example but did not relate the content to their everyday experience:

> *This lab helped me better understand how human beings manipulate matter, particularly the states of matter, to their benefit. In this lab, we manipulated solid CO_2 and brought it to a boil in a liquid state, a rare occurrence that does not usually occur outside the lab given CO_2's natural gaseous state. It led me to think of other ways in which humans manipulate states of matter, such as the melting of metals to cast products.*

In the second reflection question referring to EV, this student scored a 3 because the response included a detailed example related to their everyday experience:

> *Learning about the principles of green chemistry was indeed very interesting and useful. I am currently reading Rachel Carson's Silent Spring for another class, and the topic of green chemistry seems particularly relevant considering Carson's warnings about the misuse of chemistry to control the environment in harmful ways. Carson argues against the use of hazardous chemical pesticides, the production of which would have certainly broken the principles of green chemistry. My younger siblings have asthma and diabetes. I am questioning if their health problems could be the result of toxins in their foods or their environment.*

For question 3 relating to MU, the time issue emerged as a theme. This question scored a 1 according to the TE rubric:

Unfortunately, I have not had an opportunity to discuss the ideas I have learned outside of our chemistry class, though I will say that I have become more aware of responsible chemical production methods, and hope to use this information, not necessarily as a chemist would, but rather as a consumer would, to make better choices when purchasing products.

Recurring emergent themes related to elements of TE from each lab were also coded (Merriam, 2001). For instance, eleven of the student responses noted that 'time' was a factor when responding to the motivated use question (number three), in that they were too busy with other course work '*Simply because I have tons of homework from other classes that take [precedent] over learning these ideas on my own time*'. Or they noted the potential for future behaviors, '*I haven't done anything differently yet, but I probably will in the future along with telling people about it*'. Other themes which emerged from the data are presented in the discussion of findings section.

In the findings section that follows, a description of each green chemistry lab as it was presented and performed is given first. Rather than providing a step by step account of each lab experience, this data is meant to provide a more nuanced understanding of the pedagogical techniques that were used to introduce the laboratory content and includes any deviation from the procedures outlined in the laboratory experiment handouts. Additionally, these process data provide context for the discussion section of this study. For instance, it may be important to note that in the first lab, extraction of d-limonene, exactly half of the student lab groups were unable to extract the oil.

Findings

The findings section is organized in a way that treats each lab as a separate unit of analysis within the larger unit of the 6-week GC laboratory experience (Patton, 2002). As such, three focusing questions were used to present and interpret the TE evidence with respect to the research question: *What is the evidence that green chemistry laboratory experiments supported students' transformative experience in a first-semester general chemistry course?*

1. Which lab (if any) showed the largest effect on TEQ scores and/or reflections of TE?
2. Based on TEQ items and reflections on TE, is there evidence that some elements of TE were better supported by the green chemistry laboratory experience than others?
3. Did students' TEQ scores and/or reflections of TE increase across the 6-week green chemistry laboratory experience?

In findings for the individual labs, a description of each lab is given first. Tables are used to present the means, WSR (z), and effect size (r) results. Reflection scores based on the TE rubric are presented as frequency percentages by score (0-3) for the three elements of TE. TE findings across the larger unit of the 6-week laboratory experience are presented as TEQ composite scores on a chart comparing all three TEQ administrations (n=6). Response scores are then given as composite mean scores to understand if there is evidence that some elements of TE were better supported by individual labs. The TEQ composite scores from pre-Lab 1 to post-Lab 3, WSR (z), and effect size estimate (*r*) across the experience are also presented in a table. Reflection scores are again presented in charts as composite mean scores for all three of the labs to understand if there is evidence that some elements of TE were better supported than others across the 6-week GC experience.

TE Effects in Lab 1 Extraction of d-limonene from Lemon Peels

Lab 1, extraction of d-limonene, is a laboratory that was designed to investigate two methods of oil extraction, and to calculate and compare the percent yields of those two different methods. I chose the extraction of d-limonene lab to do first because this lab actively introduces the 12 Principles of Green Chemistry by asking the students to evaluate their experimental lab procedures and industrial methods against the 12 Principles. I began the pre-lab by having the students come to the front of the room to do a blind smell test of two items hidden in Styrofoam cups. The students were asked to identify the items based on smell. Students then went back to their lab tables and were asked to come to a consensus as to the identity of the items in the cups. All of the students responded that cup one contained some kind of citrus and cup two contained some kind of pine. I then drew the chemical structures for the molecules d-limonene (citrus) and l-limonene (pine) on the board. The students were then asked to identify the structural differences between the molecules. We then discussed how our olfactory senses could distinguish between two nearly identical molecules that were mirror images of each other. Concepts such as molecular vibrational energy and evolutionary advantages of a 'good sense of smell' came up in our discussion. We then discussed what other products use these molecules in their manufacturing processes. Responses ranged from Pine-sol, to popsicles and perfumes.

Following this activity, the 12 Principles of Green Chemistry were given as Power-point slides for the students to copy into their lab notebooks. Using the 12 Principles of Green Chemistry, students were then presented some industrial methods of d-limonene extraction and students evaluated these methods with respect to the 12 Principles. This was done together as a class, so the students understood how they would evaluate the lab procedures they were being asked to perform. Students then began the lab experiment by doing a steam distillation of the lemon peels to extract the oil, d-limonene. All of the students were successful with their steam extraction. However, many students noted that the oil was not pure in that only a small fraction of their distillation actually contained the oil and a large percent was actually water. Methods of how to treat this data were discussed. For the second week of the experiment, students were tasked with getting the solid CO_2 into its supercritical phase. This proved to be difficult for exactly half of the students. Fortunately, these students were able to see other groups get a good result. Students then calculated and compared the percent yields for each procedure. They were then asked to evaluate why using CO_2 in this lab did not violate the 12 Principles of Green Chemistry as the CO_2 was not generated or changed in this lab, only recycled.

Based on the TEQ results for Lab 1 shown in Table 3, the students endorsed that the first lab provided them with an experience which supported TE. The composite TEQ scores increased from pre-Lab 1 to post-Lab 1 giving an effect size estimate of ($r = 0.170$). Table # displays the class TEQ composite means (M), WSR (z), and effect size estimate (r) for Lab 1.

Table, 3.

Class TEQ composite mean scores (*M*), Wilcoxon-Signed Rank score (*z*), and effect size (*r*) results for pre-Lab to 1 post-Lab 1 (n=36).

$M_{\text{pre-Lab 1}}$	$M_{\text{post-Lab 1}}$	z	r
68.778	72.111	1.019	0.170

N = 18, p = 0.308

Table 4 displays the percentages of student responses by score (0, 1, 2, 3) in each of the three domains of TE. Lab 1 scores indicate that students were best prepared to discuss experiential value (EV) and expansion of perception (EP) in their reflections, and least prepared to discuss motivated use (MU) for the first green chemistry laboratory experiment, Extraction of d-limonene.

Table, 4.

Student written response score percentages by TE element (EP, EV, MU) and rubric score (0-3) for Lab 1, extraction of d-limonene (n=54).

Rubric Score	%EP	%EV	%MU
3	0	5.55	0
2	27.78	5.55	11.11
1	38.89	77.78	38.89
0	33.33	11.11	50.0

N = 18

Student response scores for expansion of perception (EP) were fairly equally distributed between the rubric scores of 0 and 2. Over a quarter (27.78%) of the students responded that the lab changed their perceptions about the world and provided a detailed example or explanation (i.e., rubric score of 2), most (38.89%) did not provide detailed answers or clearly explain, and others (33.33%) responded that the lab experience did not change their perceptions about the world. Experiential value scores (EV) indicate that most of the students (77.78%) responded that the lab was interesting and had value but did not provide examples or explain why they found it interesting or valuable. Scores show that half of the class received a score of 0 for their response to the question regarding motivated use (MU) indicating that the lab experience did not influence any behaviors outside of lab. Some students (38.89%) responded that the lab did influence behavior but did not provide examples or explain, while a few students did provide more detailed explanations.

TE Effects in Lab 2 Production and Analysis of Biodiesel

Laboratory 2 was designed for students to explore a method of biodiesel production and calculate a thermochemical heat value for their biodiesel and compare it with the thermochemical heat value of gasoline. I began this lab by showing a clip from the movie 21 Jump Street where the students are in the school parking lot talking about one of the student's cars smelling like egg rolls because it ran on leftover oil from a Chinese restaurant. We talked about if any of them had a biodiesel car or knew of anyone that did. Procedures were discussed for the first week of the experiment where students had to perform a transesterification on the cooking oil that would have to sit for a week so that the biodiesel would separate from the alcohol. The following week, students separated the biodiesel from the waste products and set up a crude water calorimeter that would serve to provide data for the thermochemical heat value calculation. Only one student did not get the biodiesel to separate because of overheating the original solution. Discussion about why steel wool was used to increase surface area of the fuel and oxygen mixture proved to be an important detail in this lab.

Table 5 displays the composite mean TEQ scores for pre-Lab 2 to post-Lab 2 indicating a small increase in TEQ scores for Lab 2, Synthesis and Analysis of Biodiesel. The effect size estimate ($r = 0.026$) reflects this small increase in TEQ scores.

Table, 5.

Class TEQ composite mean scores (*M*), Wilcoxon-Signed Rank score (*z*), and effect size (*r*) results for pre-Lab 2 to post-Lab 2 (n=36).

$M_{\text{pre-Lab 2}}$	$M_{\text{post-Lab 2}}$	z	r
67.000	67.944	0.156	0.026

$N = 18, p = 0.876$

Table 6 shows that the elements of TE which were most endorsed by the student reflection responses in this lab were expansion of perception (EP) and experiential value (EV). Again, motivated use (MU) appears to have been the least supported element of TE.

Table, 6.

Student response score percentages by TE element (EP, EV, MU) and rubric score (0-3) for Lab 2, Synthesis and Analysis of Biodiesel (n=54).

Rubric Score	% EP	% EV	% MU
3	5.56	0	0
2	22.22	11.11	27.78
1	44.44	77.78	11.11
0	27.78	11.11	61.11

N = 18

The second lab shows nearly the same pattern in response scores as the first lab, but the percentage of student responses that scored a 1 for experiential value (EV) is noticeably larger (77.78%). Again, students were unable to provide detail in their responses to the question relating to motivated use (MU); however, a few students (27.78%) received a rubric score of 2 indicating that they provided an example or explanation about how the lab influenced one or more behavior.

TE Effects in Lab 3 Solubility of Solids and Gases

This lab was designed to investigate factors affecting the solubility of solids and gases in solution. I began the first part of this lab procedure by asking students to think about how and why soda goes flat. Then, I showed a clip from the National Geographic special on the Lake Nyos disaster in Cameroon, Africa. This clip talked about the geology of Lake Nyos and the consequences (death toll) of the disaster itself. Students were asked to write their ideas about what could have caused the CO_2 gas to come out of solution in the lake over the course of the experiment. Rather than performing the first part of the procedure as a demo, students performed the procedure by lab table. They had two different water temperature beakers (cold and warm) and cold carbonated water in graduated cylinders. The cylinders were turned over in the beakers to identify which temperature condition promoted the release of the CO_2 gas more effectively. Students were then asked to write conclusions based on their observations. Other means of releasing the CO_2 were discussed, such as agitation. Students then presented their hypotheses as to why the lake Nyos disaster may have occurred. Then, I showed the rest of the clip explaining what scientists concluded about the disaster. We then discussed the consequences of a small temperature increase of global waters and the consequences of releasing CO_2 from global waters. In the second week of the experiment, students were asked to compare the solubility values for two ionic solids, a chloride and a sulfate. Their data were then compared to the solubility rules outlined in their textbooks. Toxicity values and the meaning of an LD50 were discussed as they relate to the solubility and absorption of certain compounds by the human body.

Table 7 indicates an increase in composite TEQ score means from pre-Lab 3 to post-Lab 3 which produced a larger effect size estimate ($r = 0.237$) than the other two labs. Table # displays the composite means, WSR, and effect size estimate for Lab 3.

Table, 7.

Class TEQ composite mean scores (*M*), Wilcoxon-Signed Rank score (*z*), and effect size (*r*) results for pre-Lab 3 to post-Lab 3 (n=36).

$M_{\text{pre-Lab 3}}$	$M_{\text{post-Lab 3}}$	z	r
72.944	74.278	1.423	0.237

N = 18, p = 0.155

Table 8 shows that reflection response scores to the experiential value (EV) question were similar to the other two labs but there is a potential difference in experiential value (EV) and expansion of perception (EP). MU reflection scores for this lab were significantly lower compared to the other two labs with (88.89%) of students scoring a zero on their response according to the rubric.

Table, 8.

Student response score percentages by TE element (EP, EV, MU) and rubric score (0-3) for Lab 3, Solubility of Gases and Solids (n=54).

Rubric Score	% EP	% EV	% MU
3	0	0	0
2	27.78	27.78	5.56
1	16.67	44.44	5.56
0	55.56	27.78	88.89

N = 18

Reflection scores for Lab 3, Solubility of Solids and Gases, were in fact lower overall, and MU for this lab scored the lowest of all three labs. There also appears to be a potential difference in EP and EV which breaks the pattern seen in the other two labs. Based on the TEQ effect size estimate for Lab 3, there is evidence to support the assertion that Lab 3 had the largest effect on students' TE. However, student summary reflection scores do not support this assertion, in fact reflection scores for Lab 3 were significantly lower than the other two labs with more students receiving a zero on their responses for each element than the other two labs. These data are contrary to the findings from the TEQ effect size estimates where Lab 3 produced the largest effect size ($r = 0.237$) relative to the other two labs.

TE Effects across the Labs

In order to understand the overall effect of the green chemistry laboratory experience, the composite TEQ scores were compared for pre-Lab 1 to post-Lab 3. Table 9 shows that the TEQ mean composite score from pre-Lab 1 to post-Lab 3 increased from 68.778 to 74.278 resulting in an effect size estimate of ($r = 0.185$) overall.

Table, 9.

Class TEQ composite mean scores (*M*), Wilcoxon-Signed Rank score (*z*), and effect size (*r*) results for pre-Lab to 1 post-Lab 3 (n=36).

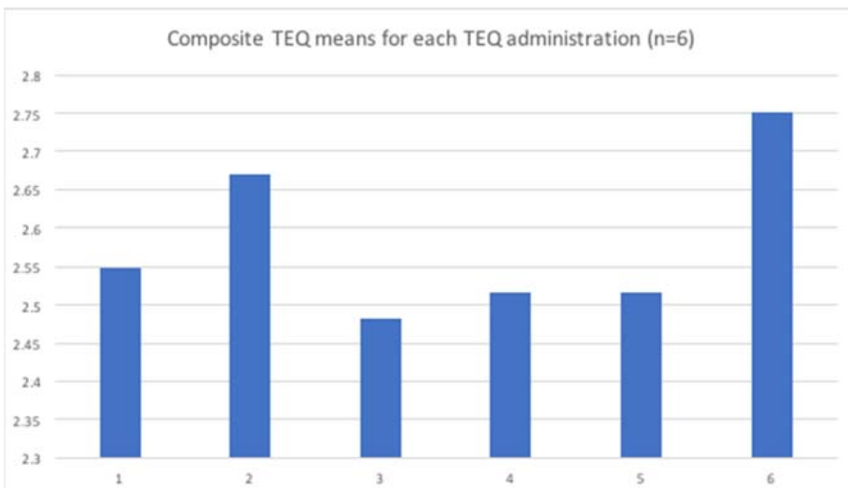
$M_{\text{pre-Lab 1}}$	$M_{\text{post-Lab 3}}$	z	r
68.778	74.278	1.107	0.185

$N = 18$, $p = 0.267$

Comparing the average TEQ Likert scores across the labs, students were more able to agree with items on the survey after Lab 3 than they were before Lab 1. Figure 2 displays the Likert data averages for all TEQ administrations. Students were more likely to disagree with questions on the pre-Lab 1 TEQ (i.e., choice < 2.5) than they were on the post-Lab 3 TEQ (i.e., choice > 2.5).

Figure, 2.

TEQ mean Likert survey scores from pre-Lab 1 to post-Lab 3.



Because there was no final reflection response that covered the scope of the green chemistry laboratory experiences, TE response scores presented in Figure 3 below are based on average reflection scores for the study population for each lab. A comparison of the average response scores across the labs reveals evidence of TE for each of the three labs. The average response scores for Lab 1 and Lab 2 were both between 2.5 and 3 indicating that students were able explain and apply with detailed examples in their reflections, but less able to provide detailed examples in their Lab 3 reflections.

Figure, 3.

Average TE reflection response scores for Lab 1, Lab 2, and Lab 3.

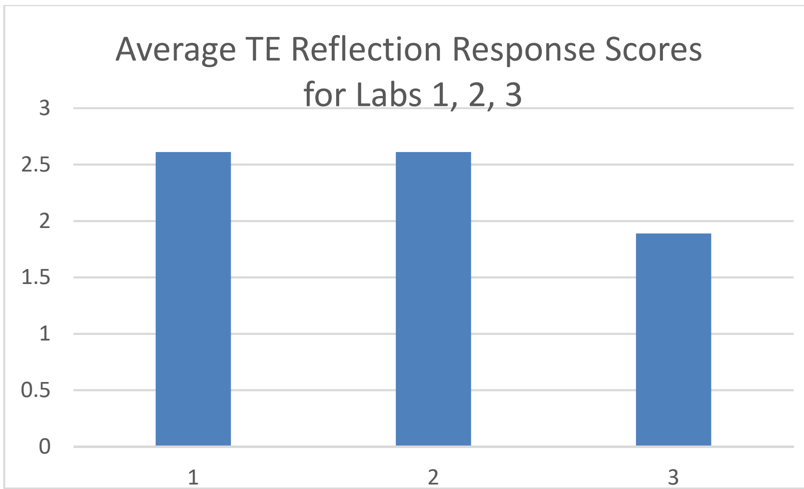
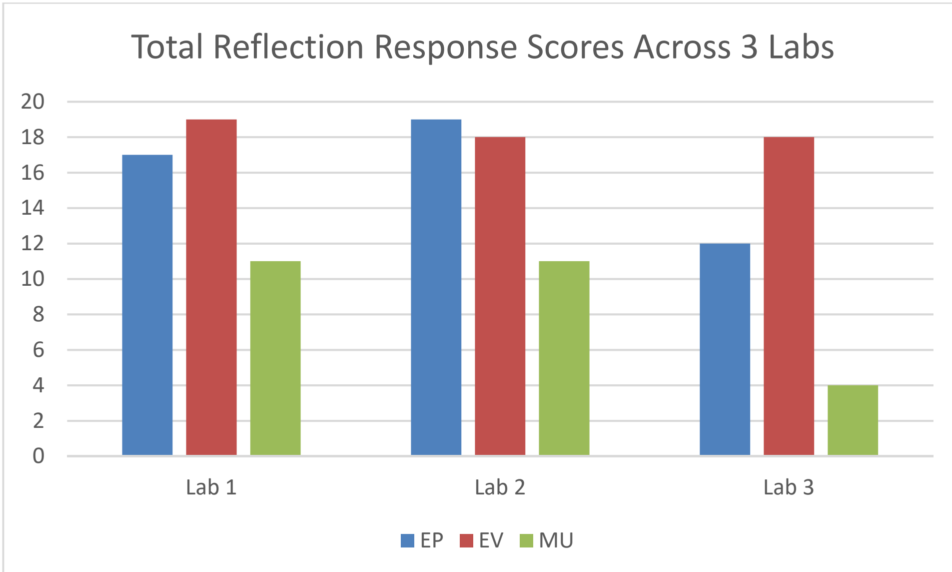


Figure 4 presents the total reflection scores for the three elements of TE for all students for all three labs. Student reflection response totals indicate that they were more likely to endorse expansion of perception (EP) and experiential value (EV) in their responses more than the element of motivated use (MU).

Figure, 4.

Elements of TE total reflection response scores for Lab 1, Lab 2, and Lab 3.



This evidence suggests that experiential value (EV) was better supported by the GC laboratory experience than either expansion of perception (EP) or motivated use (MU). Looking at the total scores for each element across the labs, student response scores were ranked highest for EV (55%) meaning that students were best able to provide detailed responses about TE for reflection question #2 for all of three of the labs. Reflection response scores indicate a pattern that students responded in more detail to the questions relating to the elements of EP and EV than MU for all three labs. However, as shown in Table 10, MU scores for Lab 1 and Lab 2 are higher than the MU score from Lab 3.

Table, 10.

Total reflection scores for elements of TE (EP, EV, and MU) by Lab.

	Lab 1	**Lab 2**	**Lab 3**
EP	17	19	12
EV	19	18	18
MU	11	11	4

Table 10 also shows that EP responses were stronger in the first two labs than the third. MU total scores were marginally lower (19.5%) meaning that students were less able to respond in detail to reflection Question #3 regarding behaviors. The MU scores from the student reflections remained consistently low compared to EP and EV for all three of the labs.

Chapter 4

In this section, transformative experience (TE), green chemistry (GC) procedures, and areas for improvement are discussed using relevant findings from the three GC experiments. Next, my leadership agenda in chemistry education is explained. Finally, implications of the results of this study for social justice with respect to motivation and retention in chemistry and directions for future research to improve chemistry teaching practice are explored.

Discussion of Findings

Based on the overall findings in this study, a credible assertion can be made that GC laboratory experiments were supportive of students' transformative experiences in general chemistry. The TEQ effect size estimates indicate small but positive effects for each lab and across the labs. Although the effect is small, Coe (2002) and others (Lazowski & Hulleman, 2016; Mintrop, 2015) point out that most intervention type research resolves a small effect but that small effects can have value when using the data for formative (i.e., improvement) purposes, or when combined with data from repeated studies in similar contexts. Experiential value (EV) appears to have been most supported according to student responses to the reflection questions. In line with other research on TE, motivated use (MU) items for out of class experiences were most difficult for the students to endorse (Koskey et al., 2017). Total reflection scores indicated no cumulative TE effect across the labs, nor were they expected to. The reflections were only done post-lab and were meant to measure whether the students' perceptions changed as a result of TE as they reflected back on the labs. Additionally, the reflection questions were designed to evidence TE by lab and no final reflection questions were given that asked about the scope of the

GC laboratory sequence. In future studies, it would be important to include a qualitative measure which asks students to reflect on their experience of the intervention as a whole.

Based on the reflection response rubric, the students were better prepared to respond in detail to questions relating to expansion of perception (EP) and experiential value (EV) over motivated use (MU). This finding is in line with other research on TE that found students were more likely to endorse questions on the TEQ related to EP and EV and least likely to endorse questions relating to MU, the behavior component of TE (Pugh et al., 2017). Why is this? MU is measured on the TEQ using action verbs and phrases like *looked for*, *talked about*, *notice*, and *use*. The TEQ contains 11 questions relating to the element of MU, 9 questions relating to the element of EV, and 7 questions relating to the element of EP, meaning that 41% of the questions on the TEQ are about MU. So why does it appear that MU questions easier for students to endorse on the TEQ and more difficult to respond to in their TE reflections? Based on their reflection responses, three theories emerged from the data. I will relate these theories to Lab 1 for clarity.

In the first lab, the procedure used a distillation apparatus for extraction to compare procedure efficiency to using liquid CO_2 as a solvent. The overall purpose of the lab was to present the students with a more efficient alternative technique that recycled carbon dioxide from the air. It appears from the student responses the connection to the larger purpose of the lab was not made, their responses for MU reflected this. In other words, their responses were scored lower because their behavior did not change in response to the experiment. But when is anyone in everyday life going to actually *use* this extraction method? Why would it be *useful* to them?

On the other hand, students who connected with the larger purpose provided rich and detailed responses in spite of the difficult procedure. This student's response seems to cover both:

> *Unfortunately, I have not had an opportunity to discuss the ideas I have learned outside of out chemistry class, though I will say that I have become more aware of responsible chemical production method, and hope to use this information, not necessarily as a chemist would, but rather as a consumer would, to make better choices when purchasing products.*

Based on this theory and the low MU reflection scores in all three labs, it is important that the connection to the larger purpose and its relevance to the lives of the students is made more apparent. This could be done according to the TTES framework by using more relevant examples and modeling how the concepts are useful and relevant in my own life. Or, it could simply be that the reflection question did not successfully convey the type of information that was sought in student responses.

Another theory about why MU responses were consistently lower concerns time. Koskey et al. (2017) note that students' TE reflections may not be accurate because they may not have had the time or opportunity to engage with concepts outside of class (Koskey et al., 2017). As found in this research, students reported that they didn't have time to *'think about the world differently'* or engage with concepts because they *'didn't come up in conversation'*. Longitudinal studies would be needed to understand if elements of students' TE did increase over a period of time, after they had more time to reflect on their experiences. This theme emerged from the MU reflection data most often. Using Lab 1 again for example, out of 18 responses to the reflection question regarding MU, 31% of the students responded in some way that they did not have time to use what they had learned in the lab; and 11% indicated the potential for future use:

> *I did not do anything different after the experiment nor did I tell anybody about the experiment. Afterwards, I did not look up any additional information or look for examples. The reason why was that I moved on to other classwork.*

Additional research is needed to understand if student reflection responses for the element of MU would be more robust if the students were given more than one week to reflect on the concepts learned in the lab.

The GC laboratory experiment procedures that were problematic may have influenced student reflection responses in a negative way. Recall in the description of the first lab that exactly half of the students did not get the CO_2 to liquefy so they did not get a result. I found that many of their reflection statements referred to this challenge and question if their reflection responses were influenced by poor results from the lab. This was noted in nearly 30% of the 54 reflection responses for this lab, pertaining most often to the question related to experiential value (EV). For this question, many student responses focused on the mechanics of not being able to get the CO_2 to liquefy, rather than about the value of the concepts in the lab:

No, the experiment was not very successful whether that was operator error or bad lemons. Seeing the CO2 reaction was very interesting I just wish we could [have] gotten a result. It was interesting learning different ways to do the same experiment.

This experiment was less exciting [than] some of the past experiments because there was little reaction and we did not get any results.

However, some students indicated in their responses to the EV question that the challenges surrounding the CO_2 liquefaction were motivating:

What I find most exciting is that once dry ice turns into a liquid its molecules are moving fast enough to be able to separate the oils from the lemon peels. I believe this experiment was exciting, it was challenging for us, but I enjoy a challenge such as this experiment.

I was interested in whether or not we would extract the essential oil with the dry ice. This was, I thought, one of the more exciting labs in trying to get the dry ice to liquefy after numerous attempts.

Overall, student reflection responses for the first experiment tended to focus on the CO_2 procedure in the experiment rather than the comparisons between extraction methods and the environmental impact of choosing one over the other. This GC experiment procedure should be revised so that students get consistent results.

The TE findings in the second experiment are interesting because I predicted that this lab would be the most engaging in terms of students' everyday experience because it used household cooking oil in the procedure, and the students were already aware of biodiesel technology. Further, I felt it had the most entertaining procedure because the students got to light their products on fire to measure the thermochemical fuel value of their product in their analyses. So, what happened in Lab 2 that made it relatively less effective than the other two labs in getting increases in the TEQ survey score? For this finding, I refer to research by Pugh et al. (2009) who contend that students may already have a conceptual understanding of a topic and the TEQ may not accurately measure growth where none is needed (Pugh et al., 2009). In other words, some of the students may have already had an accurate understanding of biodiesel production and their thinking was not transformed by what they learned in the lab. Several student reflection responses (38%) indicated that they already knew a bit about biodiesel, so perhaps some of their TEQ scores did not increase because no growth was necessary. For instance, one student wrote:

> *Through this experiment I learned about how biodiesel is made, but I already had a general understanding of what the process was.*

In future studies, it might be helpful to pre-test students' conceptual understanding of the material and compare it to their TEQ scores for a more accurate understanding of the effect size estimate. Also, after reviewing the TEQ post-Lab 2 survey, using the term 'thermochemical fuel values' in everyday experience was a poor choice of words and this question could have been written in the post-survey in more conversational terms to reflect the overall purpose of the lab, which was evaluating the efficiency of alternative fuel sources, namely biodiesel. Even though it was the chemistry concept the lab was meant to cover, the thermochemical fuel values were only used in a calculation at the very end of the procedure. This lab was designed to investigate a 'greener' fuel source but the laboratory procedure produces thick black smoke and soot when the students analyze their fuel. I found that some students remarked in their reflection responses about how dirty the biodiesel combustion was. To prevent misconceptions, it would be important in this lab to explain to students beforehand that biodiesel is a carbon-based fuel that produces emissions, but the impact on the environment is less because it is not a fossil fuel and the carbon chains are smaller which produces less CO_2.

The third lab appears to have influenced students TE the most according to the TEQ effect size estimate and the least according to the reflection scores. This finding was intriguing for two reasons. First, based on the reflection response scores for the third lab, and the contrary evidence from the TEQ effect size estimate, it would be reasonable to conclude that students were tired of writing reflection responses (i.e., fatigue effect). However, the EV score for the third lab is comparable to the other two labs. A word count of the responses indicated that students did not write any less for the third lab when compared to the other two. It should also be noted that this was the last lab of the spring semester and timing may have influenced the richness of student responses because finals were looming. For future studies, it would be important to see if reversing the order of the labs (or the reflection questions) might influence reflection scores. It must also be noted that the TEQ questionnaire was completed by the students during the scheduled laboratory session. To circumvent the fatigue effect on reflection responses, it might have been beneficial to give students dedicated time in class to write their reflection responses. Secondly, I found this lab to be the least engaging of the three labs but student reflection responses for this lab and my own casual observations indicated that they *liked* it the most. Even though the reflection response scores were low according to the rubric, several student reflection responses (48%) to the experiential value (EV) question remarked in some way about the *relevance* of the lab to everyday experience because of a new understanding about why their pop goes flat:

> *It was interesting to learn the science behind this seemingly simple idea. It was interesting to actually see the gas escape more from the warmer cylinder. This supports the idea that one would rather drink cold pop because it's not flat.*

> *This was an interesting experiment for me since I have wondered in the past what caused my pop to become flat. This lab was more exciting than a few labs since this is something that many of us had experienced in life.*

A few student responses to the expansion of perception (EP) question demonstrated how they found the lab relevant to the larger concept of warming ocean temperatures and not soda:

> *Until this lab, I had never really conceived of gases as solutes, but rather considered solids to be the only one form of solute. Our experiment with the carbonated water helped to open my eyes to the reality of dissolved gases, which enriches by understanding of the natural world. This new insight is especially useful when*

considering the complex problem of increased CO_2 emissions today and the capacity of our oceans to store and process the excess CO_2 gas.

Based on the results of this study and other published studies, transformative experience is indeed a difficult construct to measure (Koskey et al., 2016; Pugh et al. 2017; Roth & Jornet, 2014). Using a coding rubric to score reflections for the elements of TE was a valuable tool for data analysis. However, I question if students should have been given a copy of the rubric along with a detailed explanation of how their responses would be scored. This may have provided them with insight into the kind of information the reflection questions were designed to explore. Or, because the students understood the reflections would not be part of their course grade, they should have been provided with feedback on the quality and comprehensiveness of their reflection responses with another lab before data collection, or after the first lab reflection. Although the questions were designed to dissuade yes or no type responses, it was disappointing to find that many students provided only pithy responses to the questions. Other responses seemed a bit too cloying making their responses seem less personal and more performance oriented. Also, further research should be conducted to see if the order of the laboratory sequence was a factor in both the quantitative and qualitative findings. For instance, Lab 3 was scored highest on the TEQ, but student reflection responses were scored lowest for that lab based on the rubric. This low reflection score could be due to the fatigue effect (i.e., students were tired of writing reflections) or the TEQ scores may have been higher for that lab just because the students were glad it was the last one.

Further, the TEQ reflection questions should have been piloted with a similar population of students for this study before data were collected. Some questions on the TEQ appear to ask the same question and students may not have taken the time to read the questions in depth before answering. For instance, items # 6 on the pre-TEQ reads *Outside of class, I think about the properties of matter*, and item #7 reads *I find myself thinking about the properties of matter in my life outside of class.* Arguably, this is essentially the same question. In fact, degrees of engagement could be understood with just a few questions that relate to exemplary EP, EV, and MU engagement experiences because students are scoring themselves on a Likert-type scale that would provide insight into the degree of their engagement.

Like many surveys, the TEQ relies on student self-ratings of TE where students are asked to agree or disagree about their engagement with concepts ranging from in-class experiences to out-of- class experiences. It has been noted by researchers that students often do not understand the 'degree of their response' so they may score themselves lower than, or higher than, what they actually experienced. Also, Koskey et al. (2016) found that students had incongruent understandings of what was meant in the survey by 'everyday life'. For instance, some students interpreted it to mean engaging in the behavior daily outside of school, and others in school (Koskey et al., 2016). Based on these factors alone, one could argue that any survey data is inaccurate, which might also explain the contradiction in scores found in the third lab.

This study relied on practical measurement which produced an enourmous amount of data for only three labs. Using two different measurement scales and descriptive statistics, it was challenging to accurately understand the data for this small population of students. The reflection responses proved to be an extremely rich source of data, beyond the parameters of the study, that I will use for improvement purposes in the GC curriculum and TE pedagogy. Not only were misconceptions of the students revealed, but my own were as well.

Directions for Future Research

This study used a GC laboratory design based on the premise that it would impact students' TE because it frames chemistry concepts as worthwhile ideas, encourages student autonomy and agency through evaluation of traditional vs. green lab procedures, and provides for experientially anchored (i.e., relevant) instruction using laboratory materials that can be found in everyday life. Rather than focusing on what I could do to influence students' TE in chemistry, this study measured if the ideas in a GC laboratory design were meaningful enough for the students to be open for TE to occur (i.e., surrender). In future studies, it would be important to understand how I influence students' TE in chemistry. For example, was I more excited about one lab than another? Were the examples I used in one lab more relevant to the students than another? The literature contends that these pedagogical variables also influence students' TE in science (Pugh, 2011).

Pugh et al. (2009) found that transformative experience favors a mastery (i.e., developing competence) rather than a performance (i.e., demonstrating or avoiding competence) goal orientation (Pugh et al., 2009, p. 6). Here, it would be of value to understand if a mastery goal orientation influences transformative experience, or if a transformative experience promotes a mastery goal orientation. In other words, does engagement with a concept cause a TE to occur or does a TE promote engagement with a concept?

Finally, a cursory examination of individual student data in this study reveals that particular students scored consistently higher than other students in the class in both the quantitative and qualitative findings. Recall that for a TE to occur, the learner must be open to the experience. Paul (2014) contends that TE's can be difficult for some individuals because of envisioned social constraints. It would be valuable to gain a better understanding of why some students were open to the GC laboratory experiments more consistently than others. This could be done with a more extensive qualitative study where students are interviewed rather than asked to reflect on their experience in writing.

Next Steps for Leadership in Chemistry Education

The laboratories used for this study were sourced from Beyond Benign (www.beyondbenign.org). They were written and designed by teachers, for teachers to use in their 11-16 classrooms. The Beyond Benign organization was founded through the Warner Babcock Institute for Green Chemistry. John Warner, co-author of the pioneering book, *Green Chemistry: Theory and Practice* (1998), co-founded the Warner Babcock Institute and designed it an innovation factory where a maverick group of 25 full time scientists collaborate with diverse commercial industry clients to "help them improve composition and profitability of their products and production processes in line with the 12 Principles of Green Chemistry" (www.warnerbabcock.com). Their diverse clientele includes Michael J. Fox and the development of a cure for Parkinson's disease, Adidas in the production of the Ocean Shoe (a shoe with fibers spun from ocean plastic), and hair color regeneration (derived from a molecule found in insect shells).

With design and improvement as their core focus, their aims are to make products and manufacturing environmentally benign, more economically viable, and functionally equivalent to, or out-perform existing alternatives (www.warnerbabcock.com). Similar to the Hypocratic oath taken by practicing physicians, scientists practicing green chemistry have a social-justice oriented philosophy of *designing for intentional benefits rather than suffering with the unintended consequences of their actions*. This decidedly more functional approach to chemistry asks, “Why would a chemist make a hazardous substance in the first place”? It is a hopeful philosophy of practice which anticipates the human and environmental impact first.

Much like the improvement research paradigm, the design principles in the work being done at the Institute necessitates a collaboration between scientists from diverse fields of study working on the design of greener alternatives. Or, as John Warner stated, “a molecule doesn’t know what industry it is in” (John Warner, personal communication, July 14, 2017). The philosophy of the group, as stated earlier, is a hopeful one. They believe that green chemistry is a burgeoning market where industries want to be green but there just are not a lot of alternatives available. In other words, the Institute sees their work as supplying those alternatives to their clients. By their estimates, only 10% of potential greener practices have been invented. Pedagogically speaking, this understanding may catalyze a desire for invention and creativity in my students for a field that is commonly taught like it is a ‘classic’ (Anastas & Eghblai, 2009).

Beyond Benign is the educational outreach organization which evolved from the Warner Babcock Institute for Green Chemistry. From the fundamental question driving the Instititute, “Why would a chemist make a hazardous substance in the first place”, evolved the question, “How do we make better chemists instead” (John Warner, personal communication, July 13, 2017)? Because of a distinct personally transformative experience, John Warner recognized that toxicology is not a course found in most undergraduate chemistry degree programs. John Warner shared with me a very important transformative experience he underwent early on in his career that resonated with me both professionally and personally. As an up and coming chemist and professor at Boston University, his son died of a rare birth defect thought to have been caused by environmental exposure to a toxic chemical. As the patent holder on hundreds of molecules, he questioned how many such incidents were caused by his 'creations'. This event permanently transformed his perspective on the purpose of his work and his life. It was through this personal paradigm shift that the Beyond Benign group was founded. Although it now sustains itself through its own funding, the Beyond Benign group shares workspace with the scientists at the Institute. The scientists collaborate with the educators to design the laboratories because they recognize the importance of growing the next generation of green scientists.

Because of my current research agenda, I found the Beyond Benign group through their free online chemistry laboratory curriculum. I applied to be one of the 15 Lead chemistry teachers from around the country who are committed to teaching through the 12 principles of green chemistry. As a selected member of this 'networked improvement community', I am contracted to develop curriculum, present GC demonstrations at workshops and conferences, and committed to educating others about the design principles of green chemistry.

Implications for Social Justice

The findings in this study have potential implications for social justice on the individual level, curricular level, and at the societal level. Recall that the present gate-keeper design of many general chemistry courses acts as a barrier to progression for many competent students in STEM fields of study (Gasiewski et al., 2012). And, while most chemistry courses are taught within the constructivist paradigm, they afford students with little autonomy because of the standardized body of chemistry knowledge (Osborne & Dillon, 2008). Further, students who do not identify with stakeholder agendas for STEM education resist acculturation into STEM fields (Aikenhead, 2006). A relevant chemistry context that is thought to overcome these barriers is a context which leverages the personal development of the student by emphasizing both personal and societal consequences for learning chemistry (McClaren, 2015; Stuckey et al., 2013). It is believed that a consequences driven approach to chemistry can positively influence students' agentive engagement with the content (Sinatra et al., 2015). Because agency surrounding issues of sustainability are usually discussed in terms of the proxy agent making decisions (i.e., techno-scientific solutions) not the individual (Hufnagel et al., 2017), green chemistry could potentially increase student perceptions of agency and autonomy in chemistry. Green chemistry can be understood as chemistry *in practice* (i.e., education for sustainable development), rather than chemistry *as practice* (i.e., education about sustainable development), which shifts that agency and autonomy back to the individual (Penuel, 2014).

Transformative experience is a motivational construct which focuses on how agentive student engagement with concepts influences student experiences (Pugh, 2002; 2011). It is believed that the aggregate quality of small transformative experiences can lead to transformational learning, or personal paradigm shifts (Heddy & Pugh, 2015). While it is understood that instructors cannot cause a transformative experience in their students, it has been found that students are more likely to undergo a transformative experience if they believe what they are learning has a meaningful purpose (Wong, 2007). Design implies intention, and a chemistry context designed with a purposeful and meaningful intention could potentially increase student motivation and retention in chemistry. This could have far reaching systemic and cyclical benefits for the STEM disciplines and for the environment because chemistry and STEM would attract students with socially just inspired intentions. These intentions could then be operationalized in the STEM workforce and improve the environmental conditions that marginalized groups are forced to endure. In this way, green chemistry and STEM fields can be thought of as a form of public scholarship, where science is practiced for civic engagement (Rudolph & Horibe, 2015).

References

Aikenhead, G.S. (2000). Renegotiating the culture of school science. In R. Millar, J. Leach, & J. Osborne (Eds.), *Improving science education* (pp. 1-22). Canada: Open University Press.

Aikenhead, G.S. (2006). *Science Education for everyday life: Evidence-based practice*. New York, NY: Teachers College Press.

Aikenhead, G.S., Jegede, O.J. (1999). Cross-cultural science education: A cognitive explanation of a cultural phenomenon. *Journal of Research in Science Teaching*, 36(3), 269-287.

Anastas, P. & Eghblai, N. (2009). Green chemistry: Principles and practice. *Chemical Society Reviews*, 39, 301-312. doi: 10.1039/b918763b

Andraos, J. & Dicks, A.P. (2012). Green chemistry teaching in higher education: a review of effective practices. *Chemistry Education Research and Practice*, 13, 69-79.

Bandura, A. (1977). Self-efficacy: Toward a unifying theory of behavioral change. *Psychological Review*, 84(2), 191-215.

Bandura, A. (1989). Social cognitive theory. In R. Vasta (Ed.), *Annals of child development.* Six theories of child development (Vol. 6, pp. 1-60). Greenwich, CT: JAI Press.

Bandura, A. (1991). Social cognitive theory of self-regulation. *Organizational Behavior and Human Decision Processes*, 50, 248-287.

Bandura, A. (1998). Exploration of fortuitous determinants of life paths. *Psychological Inquiry*, 9(2), 95-115.

Bandura, A. (2000). Exercise of human agency through collective efficacy. American Psychological Society, *Current Directions in Psychological Science*, 9(3), 75-78.

Bandura, A. (2001). Social cognitive theory: An agentic perspective. *Annual Review of Psychology*, 52, 1-26.

Bandura, A. (2002). Environmental sustainability by sociocognitive deceleration of population growth. In P. Schmuch & W. Schultz (Eds.), *The psychology of sustainable development* (pp. 209-238). Dordrecht, the Netherlands: Kluwer.

Bandura, A. (2006). Going global with social cognitive theory: From prospect to paydirt. In Donaldson, S.I., Berger, D.E. & Pezdek, K. (Eds.), *Applied*

Psychology: New Frontiers and Rewarding Careers (pp. 53-79). Yahweh, NJ: Lawrence Erlbaum.

Bandura, A. (2007). Impeding ecological sustainability through moral disengagement. *International Journal of Sustainable Development*, 2(1), 8-38.

Barab, S. & Squire, K. (2004). Design based research: Putting a stake in the ground. *The Journal of Learning Sciences*, 13(11), 1-14.

Barry, B. (2005). *Why social justice matters.* Cambridge: Polity Press.

Beach, E.S., Cui, Z. & Anastas, P. (2009). Green chemistry: A design framework for sustainability. *Energy and Environmental Science*, 2, 1038-1049. doi: 10.1039/b904997p

Belt, S.T., Leisvik, M.J., Hyde, A.J. & Overton, T.L. (2005). Using a context-based approach to undergraduate chemistry teaching-a case study for introductory physical chemistry. *Chemistry Education Research and Practice*, 6(3), 166-179.

Brickhouse, N. W. (2001). Embodying science: A feminist perspective on learning. *Journal of Research in Science Teaching*, 38(3), 282-295.

Britner, S.L. & Pajares, F. (2006). Sources of self-efficacy beliefs of middle school students. *Journal of Research in Science Teaching*, 43(5), 485-499.

Brown, L.R. (2008). *Plan 3.0: Mobilizing to save civilization*. New York: WW Norton & Company.

Bryk, A.S., Gomez, L.M., & Grunow, A. (2010). Getting ideas into action: Building networked improvement communities in education. Retrieved from http://www.carnegiefoundation.org/spotlight/webinar-bryk-gomez-building-networked-improvement-communities-in-education, January 16, 2017.

Bryk, A.S., Yeager, D.S., Hausman, H., Muhich, J., Dolle, J.R., Grunow, A., LeMahieu, P., Gomez, L. (2013). Improvement research carried out through networked communities: Accelerating learning about practices that support more productive student mindsets. *A White Paper prepared for the White House meeting on Excellence in Education: The importance of Academic Mindsets*. Draft, with permission.

Bryk, A.S., Gomez, L.M., Grunow, A. & LeMahieu, P.G. (2015). *Learning to improve: How America's schools can get better at getting better*. Cambridge, MA: Harvard Education Press.

Burchfield, (1990). *Lord Kelvin and the age of the earth*. University of Chicago Press.

Burmeister, M. & Eilks, I. (2013). An understanding of sustainability and education for sustainable development among German student teachers and trainee teachers of chemistry. *Science Education International*, 24(2), 167-194.

Burmeister, M., Rauch, F. & Eilks, I. (2012). Education for Sustainable Development (ESD) and chemistry education. *Chemistry Education Research and Practice*. doi: 10.1039/C1RP90060A

Caruana, V., Woodrow, K. & Perez, L. (2015). Using the learning activities survey to examine transformative learning experience in two graduate teacher preparation courses. *InSight: A Journal of Scholarly Teaching*, 10, 25-34.

Coe, R. (2002). It's the effect size stupid: What effect size is and why it's important. *Paper presented at the British Educational Research Association Annual Conference*. Exeter, England, 12-14 September, 2002.

Coll, R.K., Dalgety, J., Jones, A. & Salter, D. (2001). Developing a survey instrument to evaluate tertiary chemistry students' attitudes and learning experiences. *Chemistry in New Zealand*, 42-47.

Coll, R.K., Dalgety, J. & Salter, D. (2002). The development of the chemistry attitudes and experiences questionnaire (CAEQ). *Chemistry Education Research and Practice in Europe*, 3(1), 19-32.

Creswell, J.W., Plano Clark, V.L. (2011). *Designing and conducting mixed methods research.* Thousand Oaks, CA: Sage Publications.

Cooper, M. M. (2013). Chemistry and the next generation science standards. *Journal of Chemical Education*, 90, 679-680. doi: 10.1021/ed400284c

De Boer, G.E. (1991). *A history of ideas in science education: Implications for practice*. New York, NY: Teachers College.

De Boer, G.E. (2000). Scientific literacy: Another look at its historical and contemporary meanings and its relationship to science education reform. *Journal of Research in Science Teaching*, 37(6), 582-601.

De Jong, O. (2006). Context-based chemical education: How to improve it? *Proceedings from the 19th ICCE: XX*, Seoul, Korea:

De Jong, O. & Talanquer, V. (2015). Why is it relevant to learn the big ideas in chemistry at school? In I. Eilks & A. Hofstein (Eds.), *Relevant chemistry education: From theory to practice* (pp. 11-31). Publisher

Dewey, J. (1938). *Experience and education.* Kappa Delta Pi. Free Press, New York: Free Press.

Dewey, J. (1944). *Democracy and education*. New York, NY: The Free Press.

Duschl, R.A. & Osborne, J. (2002). Supporting and promoting argumentation discourse in science education. *Studies in Science Education*, 38, 39-72.

Eccles, J.S. (2005). Subjective task value and the Eccles et al. model of achievement related choices. In A.J. Elliot & C.S. Dweck (Eds.), *Handbook of competence and motivation* (pp. 105-121). New York: The Guilford Press.

Eilks, I. & Hofstein, A. (2015). *Relevant chemical education: From theory to practice*. Rotterdam: Sense Publishing.

Eilks, I. & Rauch, F. (2012). Sustainable development and green chemistry in chemistry education. *Chemistry Education Research and Practice*, 13, 57-58. doi: 10.1039/c2rp90003c

Feierabend, T. & Eilks, I. (2010). Raising students' perception of the relevance of science teaching and promoting communication and evaluation capabilities using authentic and controversial socio-scientific issues in the framework of climate change. *Science Education International*, 21(3), 176-196.

Ferrel, B. & Barbera, J. (2015). Analysis of students' self-efficacy, interest, and effort beliefs in general chemistry. *Chemistry Education Research and Practice*, 16, 318-337. doi: 10.1039/C4RP00152D

Fishman, B.J., Penuel, W.R., Allen, A.R., Cheng, B.H. & Sabelli, N. (2013). Design-based implementation research: An emerging model for transforming the relationship of research and practice. *National Society for the Study of Education*, 112(2), 136-156.

Flannery, T. (2005). *The weather makers: How man is changing the climate and what it means to life on Earth.* New York: Grove Press.

Friere, P. (1972). *Pedagogy of the oppressed*. New York: Herder & Herder.

Galloway, K.R., Malakpa, Z. & Bretz, S.L. (2016). Investigating affective experiences in the undergraduate chemistry laboratory: Students' perceptions of control and responsibility. *Journal of Chemical Education*, 93, 227-238.

Gasiewski, J.A., Eagan, M.K., Garcia, G.A., Hurtado, S., & Chang, M.J. (2012). From gatekeeping to engagement: A multicontextual, mixed method study of student academic engagement in introductory STEM courses. Res Higher Educ., 53(2), 229-261. doi: 10.1007/s11162-011-9247-y

Gelbspan, R. (2004). *Boiling point: how politicians, big oil and coal, journalists and activists are fueling the climate crisis-and what we can do to avert disaster*. New York, NY: Basic Books.

Giamellaro, M. (2014). Science learning and levels of contextualization. Proceedings from NARST 2014: *NARST Annual International Conference*. Pittsburgh, PA: XX. Retrieved September 29, 2016. https://researchgate.net/publication/280960133

Gilbert, J.K., Justi, R., Van Driel, J.H., De Jong, O. & Treagust, D.F. (2004). Securing a future for chemical education. *Chemistry Education: Research and Practice*, 5 (1), 5-14.

Girod, M., Twyman, T. Wojcikiewicz, S. (2010). Teaching and learning for transformative, aesthetic experience. *Journal of Science Teacher Education*. doi: 10.1007/s10972-009-9175-2

Gorski, P.C. (2013). *Reaching and teaching students in poverty*. New York: Teachers College Press.

Gutierrez, K.D. & Penuel, W.R. (2014). Relevance to practice as a criterion for rigor. *Educational Researcher*, 43(1), 19-23. doi: 10.3102/0013189X13520289

Gutierrez K.D. & Vossoughi, S. (2010). Lifting off the ground to return again anew: Mediated praxis, transformative learning, and social design experiments. *Journal of Teacher Education*, 61(1-2), 100-117. doi: 10.1177/0022487109347877

Harackiewicz, J.M. & Hulleman, C.S. (2009). The importance of interest: The role of achievement goals and task values in promoting the development of interest. *Social and Personality Psychology Compass*, 4(1), 42-52. doi: 10.1111/j.1751-9004.2009.00207.x

Harackiewicz, J.M., Tibbetts, Y., Canning, E. & Hyde, J.S. (2014). Harnessing values to promote motivation in education. Advances in Motivation and Achievement, 18, 71-105.

Heddy, B.C. & Pugh, K.J. (2015). Bigger is not always better: Should educators aim for big transformative learning events or small transformative leaning experiences? *Journal of Transformative Learning*, 3(1), 52-58. Retrieved from http://jotl.uco.edu

Heddy, B.C. & Sinatra, G.M. (2013). Transforming misconceptions: Using transformative experience to promote positive affect and conceptual change in students learning about biological evolution. *Science Education*, 97(5), 723-744.

Heddy, B.C., Sinatra, G.M., Seli, H., Taasoobshirazi, G. & Mukhopadhyay (2016). Making learning meaningful: Facilitating interest development and transfer in at-risk college students. *Educational Psychology.* doi:10.1080/01443410.2016.1150420

Hofstein, A. & Mamlok-Naaman, R. (2011). High-school students' attitudes toward and interest in learning chemistry. *Educacion Quimica, 1-13.* ISSNE1870-8404

Holbrook, J. (2005). Making chemistry teaching relevant. *Chemical Education International*, 6(1), 1-12. Retrieved from http://www.iupac.org/publications/cei

Horowitz, G., Rabin, L.A., & Brodale, D.L. (2013). Improving student performance in organic chemistry: Help seeking behaviors and prior chemistry aptitude. *Journal of Scholarship of Teaching and Learning*, 13(3), 12-133.

Hufnagel, E., Kelly, J.G. & Henderson, J.A. (2017). How the environment is positioned in the Next Generation Science Standards: a critical discourse analysis. *Environmental Education Research*, 0(0), 1-23.

Hulleman, C.S. & Godes, O., Hedricks, B.L. & Harackiewicz, J.M. (2010). Enhancing interest and performance with a utility value intervention. *Journal of Educational Psychology*. doi: 10.1037/a0019506

Hulleman, C.S. & Harackiewicz, J.M. (2009). Promoting interest and performance in high school science classes. *Science*, 326, (5958), 1410-1412. Retrieved from http://science.sciencemag.org/

Jegede, O.J. & Aikenhead, G.S. (1999). Transcending cultural borders: Implications for science teaching. *Journal for Science and Technology Education*, 17(1), 45-66.

Juntunen, M.K. & Aksela, M.K. (2014). Education for sustainable development in chemistry-challenges, possibilities and pedagogical models in Finland and elsewhere. *Chemistry Education Research and Practice*, 15, 488-500. doi: 10.1039/c4rp00128a

Kan, A. & Akbas, A. (2006). Affective factors that influence chemistry achievement (attitude and self-efficacy) and the power of these factors to predict chemistry achievement. *Journal of Turkish Science Education*, 3(1), 76-85.

Karpudewan, M., Ismail, Z. & Roth, W.-M. (2012). Fostering pre-service teachers' self-determined environmental motivation through green chemistry experiments. *Journal of Science Teacher Education*, 23(6), 673-696.

Karpudewan, M., Roth, W.M., & Ismail, Z. (2015). The effects of green chemistry on secondary school students' understanding and motivation. *The Asia-Pacific Education Researcher*, 24, 35-43. doi: 10.1007/s40299-013-0156-z

Kennedy, R.F. (2005). *Crimes against nature: How George W. Bush and his corporate pas are plundering the country and hijacking our democracy*. New York, NY: Harper Collins.

Klinshirn, M.A. & Spessard, G.O. (2009). Integrating green chemistry into the introductory chemistry curriculum. *Green Chemistry Education ACS Symposium Series*, Vol. 1011Chapter 5, pp 79–92. doi: 10.1021/bk-2009-1011.ch005

Koskey, K.L., Sondergeld, T.A., Stewart, V.C., & Pugh, K.J. (2016). Applying the mixed methods instrument development and construct validation process: The transformative experience questionnaire. *Journal of Mixed Methods Research*, 1-28. doi: 10.1177/1558689816633310

Kuhn, T.S. (1962). *The structure of scientific revolutions*. University of Chicago Press.

Kurbanoglu, N.I. & Akin, A. (2010). The relationship between university students' chemistry laboratory anxiety, attitudes, and self-efficacy beliefs. *Australian Journal of Teacher Education (online)*, 35(8), 48-59. Retrieved April 11, 2016.

Lareau, A. (2011). *Unequal childhoods: class, race, and family life.* Los Angeles: The Regents of the University of California.

Lazowski, R.A. & Hulleman, C.S. (2016). Motivation interventions in education: A meta-analytic review. *Review of Educational Research*, 86(2), 602-640. doi: 10.3102/0034654315617832

Lemke, J.L. (2000). Articulating communities: Sociocultural perspectives on science education. *Journal of Research in Science Teaching*, 38(3), 296-316.

Lewis, C. (2015). What is improvement science? Do we need it in education? *Educational Researcher*, 44(1), 54-61.

Mammino, L. (2015). A great challenge of green chemistry education: The interface between provision of information and behavior patterns. *Worldwide Trends in Green Chemistry Education*. V. Gomez, V. Zuin, & L. Mammino (Eds.) doi: 10.1039/9781782621942-00001

Manchanayakage, R. (2013). Designing and incorporating green chemistry courses at a liberal arts college to increase students' awareness and interdisciplinary collaborative work. *Journal of Chemical Education*, 90, 1167-1171. doi: dx.doi.org/10.1021/ed300468r

Mandler, D., Mamlok-Naaman, R., Blonder, R., Yayon, M. & Hofstein, A. (2012). High-school chemistry teaching through environmentally oriented curricula. *Chemistry Education Research and Practice*, 13, 80-92. doi: 10.1039/c1rp90071d

Merriam, S.B. (2001). *Qualitative research and case study applications in education*. San Fransico, CA: Jossey-Bass.

Mezirow, J. (1991). *Transformative dimensions of adult learning*. San Francisco, CA: Jossey-Bass.

Mintrop, R. (2016). *Design-based school improvement: A practical guide for educators*. Cambridge, MA: Harvard Education Press.

Movahedzadeh, F. (2011). Improving students' attitude toward science through blended learning. *Science Education and Civic Engagement*, 3(12), 1-7. Retrieved from http://seceij.net/seceij/summer11/movahedzadeh_im.html.

Osborne, J., Simon, S. & Collins, S. (2003). Attitudes towards science: A review of the literature and its implications. *International Journal of Science Education*, 25(9), 1049-1079.

Paul, L.A. (2014). *Transformative experience*. Oxford University Press.

Pelletier, L.G., Dion, S., Tuson, K. & Green-Demers, I. (1999). Why do people fail to adopt environmental protective behaviors? Towards a taxonomy of environmental amotivation. *Journal of Applied Social Psychology*, 29(12), 2481-2504.

Penuel, W.R. (2014). Studying science and engineering learning in practice. *Cultural Studies of Science Education*. XX doi: 10.1007/s11422-014-9632-x

Pintrich, P.R. (2003). A motivational science perspective on the role of student motivation in learning and teaching contexts. *Journal of Educational Psychology*, 95(4), 667-686. doi: 10.1037/0022-063.95.4.667

Pugh, K.J. (2002). Teaching for idea-based, transformative experiences in science: An investigation of the effectiveness of two instructional elements. *Teachers College Record*, 104(6), 1101-1137.

Pugh, K.J. (2011). Transformative experience: An integrative construct in the spirit of Deweyan pragmatism. *Educational Psychologist*, 46(2), 107-121.

Pugh, K.J., Bergstrom, C.M., & Spencer, B. (2017). Profiles of transformative engagement: Identification, description, and relation to learning and instruction. *Science Education*, XX(x), 1-30.

Pugh, K. J., Linnenbrink-Garcia, L., Koskey, K. L. K., Stewart, V. C., & Manzey, C. (2010). Motivation, learning, and transformative experience: A study of deep engagement in science. *Science Education*, 94 (1), 1-28. doi: 10.1002/sce.20344

Roth, W.M. & Jornet, A. (2014). Towards a theory of experience. *Science Education*, 98, 106-126. doi: 10.1002/sce.21085

Roth, W.M. & Lee, S. (2004). Science education as/for participation in the community. *Science Education*, 88, 263-291.

Roth, W.M. & Lee, S. (2007). Vygotsky's neglected legacy: Cultural-historical activity theory. *Review of Educational Research*, 77 (2), 186-232.

Rudolph, J.L. (2000). Reconsidering the 'nature of science' as a curriculum component. *Journal of Curriculum Studies*, 32 (3), p. 403-419.

Rudolph, J.L. (2007). An inconvenient truth about science education. *Teachers College Record*. Retrieved on November 23, 2015, from https://science.madison.k12.wi.us/files/science/Rudolph_article.pdf

Rudolph, J.L. (2014a). Why understanding science matters: The IES research guidelines as a case in point. *Education Researcher*, 43(1), 15-18.

Rudolph, J.L. (2014b). Dewey's "science as a method" a century later: Reviving science education for civic ends. *American Educational Research Journal*, 51(6), 1056-1083. doi: 10.3102/0002831214554277.

Rudolph, J.L. & Horibe, S. (2016). What do we mean by science education for civic engagement? *Journal of Research in Science Teaching*, 53(6), 805-820.

Ryan, R.M. & Deci, E.L. (2000). Self-determination theory and facilitation of intrinsic motivation, social development, and well-being. *American Psychologist*, 55(1), 68-78.

Seymour, E. & Hewitt, N.M. (1997). *Talking about leaving: Why undergraduates leave the sciences*. Boulder, CO: Westview Press.

Schrieber, J. & Asner-Self, K. (2011). *Educational research.* Hoboken, NJ: John Wiley & Sons, Inc.

Sinatra, G.M, Heddy, B.C. & Lombardi, D. (2015). The challenges of defining and measuring student engagement in science, *Educational Psychologist*, 50(1), 1-13.

Southerland, S.A., Gadsen, V.L. & Herrington, C.D. (2014). Editor's introduction: What should count as quality education research? Continuing the discussion. *Educational Researcher*, 43(1), 7-8.

Stuckey, M., Sperling, J., Mamlok-Namman, R., Hofstein, A. & Eilks, I. (2015). The societal component in a model of relevance in science education. *Relevant* *chemistry education: From theory to practice* (pp. 245-261), I. Eilks & A. Hofsein (Eds.). Rotterdam: Sense Publishers.

Sjostrom, J., Rauch, F. & Eilks, I. (2015). Chemistry education for sustainability. *Relevant chemistry education: From theory to practice* (pp. 163-184) I. Eilks & A. Hofstein (Eds.). Rotterdam: Sense Publishers.

Taber, K.S. (2015). Epistemic relevance and learning chemistry in an academic context. *Relevant chemistry education: From theory to practice* (pp. 79-100). I. Eilks & A. Hofstein (Eds.), Rotterdam: Sense Publishers.

Talanquer, Vicente (2013). Chemistry education: Ten facets to shape us. *Journal of Chemical Education*, 90(7), 832-838. doi: dx.doi.org/10.1021/ed300881v

Tan, E. & Barton, A.C. (2007). Unpacking science for all through the lens of identities-in-practice: the stories of Amelia and Ginny. *Cultural Studies of Science Education*. doi: 10.1007/511422-007-9076-7

Tro, N.J. (2014). *Chemistry: Structure and properties*. Pearson Education.

Tujillo, G. & Tanner, K.D. (2014). Considering the role of affect in learning: Monitoring students' self-efficacy, sense of belonging, and science identity. *CBE Life Science Education*, 13(1), 6-15.

Van Aalvasort, J. (2004). Activity theory as a tool to address the problem of chemistry's lack of relevance in secondary school chemical education. *International Journal of Science Education*, 26(13), 1635-1651.

Villafane, S.M., Garcia, C.A. & Lewis, J.E. (2014). Exploring diverse students' trends in chemistry self-efficacy throughout a semester of college-level preparatory chemistry. *Chemistry Education Research and Practice*, 15, 114-127.

Watkins, J. & Mazur, E. (2013). Retaining students in science, technology, engineering, and mathematics (STEM) majors. *Journal of College Science Teaching*, 42 (5), 36-41.

Wardencki, W. & Namiesnik, C.J. (2005). Green chemistry -current and future issues. *Polish Journal of Environmental Studies*, 14(4), 389-395.

Wolfe, J. (2012). The father of green chemistry. *Forbes*. Retrieved Dec. 16, 2015 from https://www.forbes.com/sites/joshwolfe/2012/02/02/the-father-of-green-chemistry/#4efa26e3f0cf

Wong, D. (2007). Beyond control and rationality: Dewey, aesthetics, motivation, and educative experiences. *Teachers College Record*, (109)1, 192-220.

Woodhouse, E.J. & Breyman, S. (2004). Green chemistry as social movement? *Science, Technology, & Human Values*, xx (x), 1-24. doi: 10.1177/016223904271726

Yeager, D., Bryk, A., Muhich, J., Hausman, H., Morales, L. (2017). Practical Measurement. *Carnegie Foundation for the Advancement of Teaching*. Draft, with permission, Feb. 2, 2017, D.S. Yeager.

Zimmerman, H.T., & Bell, P. (2012). Everyday expertise: Learning within and across formal and informal settings. In *Theoretical foundations of learning environments* (2nd ed., pp. 223-241). New York, NY: Routledge.

Appendix A

The 12 Principles of Green Chemistry

1. **Prevention**

   It is better to prevent waste than to treat or clean up waste after it has been created.

2. **Atom Economy**

   Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.

3. **Less Hazardous Chemical Syntheses**

   Wherever practicable, synthetic methods should be designed to use and generate substances that possess little or no toxicity to human health and the environment.

4. **Designing Safer Chemicals**

   Chemical products should be designed to affect their desired function while minimizing their toxicity.

5. **Safer Solvents and Auxiliaries**

   The use of auxiliary substances (e.g., solvents, separation agents, etc.) should be made unnecessary wherever possible and innocuous when used.

6. **Design for Energy Efficiency**

   Energy requirements of chemical processes should be recognized for their environmental and economic impacts and should be minimized. If possible, synthetic methods should be conducted at ambient temperature and pressure.

7. **Use of Renewable Feedstocks**

   A raw material or feedstock should be renewable rather than depleting whenever technically and economically practicable.

8. **Reduce Derivatives**

   Unnecessary derivatization (use of blocking groups, protection/ deprotection, temporary modification of physical/chemical processes) should be minimized or avoided if possible, because such steps require additional reagents and can generate waste.

9. **Catalysis**

   Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.

10. **Design for Degradation**

    Chemical products should be designed so that at the end of their function they break down into innocuous degradation products and do not persist in the environment.

11. **Real-time analysis for Pollution Prevention**

    Analytical methodologies need to be further developed to allow for real-time, in-process monitoring and control prior to the formation of hazardous substances.

12. **Inherently Safer Chemistry for Accident Prevention**

    Substances and the form of a substance used in a chemical process should be chosen to minimize the potential for chemical accidents, including releases, explosions, and fires.

Anastas, P. T.; Warner, J. C. *Green Chemistry: Theory and Practice*, Oxford University Press: New York, 1998, p. 30. Retrieved from the ACS website with active links (www.acs.org).

Appendix B

Student Consent IRB form

DUQUESNE UNIVERSITY

600 FORBES AVENUE ♦ PITTSBURGH, PA 15282

CONSENT TO PARTICIPATE IN A RESEARCH STUDY

TITLE:	EFFECTS OF A GREEN CHEMISTRY LABORATORY DESIGN ON FIRST SEMESTER GENERAL CHEMISTRY STUDENTS' TRANSFORMATIVE EXPERIENCES IN CHEMISTRY
INVESTIGATOR:	Lurea J. Doody, Doctoral Candidate School of Education doodyl@duq.edu
ADVISOR (Doctoral Chair):	Amy Olson Assistant Professor Duquesne University School of Education Department of Foundations and Leadership 412.396.5712 /olsona@duq.edu
SOURCE OF SUPPORT:	This study is being performed as partial fulfillment of the requirements for the doctoral degree in Educational Leadership in the School of Education at Duquesne University.
PURPOSE:	You are being asked to allow for the use of your de-identified completed course work to be used in a research project which seeks to investigate the impact of a green chemistry laboratory design on transformative experience in chemistry. In order to qualify for participation, you must be enrolled in CHE121 during the Spring semester 2017.

PARTICIPANT PROCEDURES: Participants allow for the use of de-identified materials based on student work, already completed in the course, as a source of data for the study. The researcher (Professor Doody) will not know if you are a participant or non-participant until the course has ended.

These are the only requests that will be made of you.

RISKS AND BENEFITS: There are minimal risks no greater than those encountered in everyday life. Your participation or non-participation in this research will not affect your student status or your evaluation as a student. Your grade will in no way be affected if you choose not to participate.

Although there are no direct benefits in participating in this study, other students may benefit from the compilation of your input on the green chemistry laboratory design. Given the importance of transformative experience on student motivation and engagement, your participation will assist me, and may assist other chemistry instructors, in their efforts to improve the general chemistry experience.

COMPENSATION: No monetary compensation or incentive will be provided and participation in the study will require no monetary cost to you.

CONFIDENTIALITY: Your participation in this study and any information that you provide will be kept confidential at all times and to every extent possible. Your name will never appear on any survey or study documents. Written data used in the study will be made anonymous. All written and electronic forms of study materials will be kept secure. Your responses will only appear in statistical data summaries. All study information will be stored in a locked file in the researcher's home office for five years after the completion of the research and then destroyed. Non-participant data will be destroyed at the end of the semester.

RIGHT TO WITHDRAW: You are under no obligation to participate in this study and are free to withdraw consent at any time by notifying Dr. Marietta Wright: mwright@waynesburg.edu

SUMMARY OF RESULTS: A summary of the results of this research will be supplied to you, at no cost, upon request by emailing: doodyl@duq.edu

VOLUNTARY CONSENT: I have read the above statements and understand what is being requested of me. I also understand that my participation is voluntary I am free to withdraw my consent at any time, for any reason by notifying Dr. Marietta Wright. On these terms, I certify that I am willing to participate in this research project by allowing for the use of my de-identified, completed course materials as a source of data for the study.

I understand that should I have any further questions about my participation in this study, I may contact LUREA J DOODY email at: doodyl@duq.edu.
Should I have questions regarding protection of human subject issues, I may call Dr. David Delmonico, Chair of the Duquesne University Institutional Review Board, at 412.396.4032 or email: Delmonico@duq.edu

.

____ __________________
Participant's Signature Date

____ __________________
Researcher's Signature (Proxy-Agent) Date

Appendix C

The Transformative Experience Questionnaire (TEQ) Properties of Matter Form

Adapted with permission: Koskey, K., Stewart, V., Sondergeld, T., & Pugh, K. J. (2016). Applying the mixed methods instrument development and construct validity process: The case of the transformative experience questionnaire. *Journal of Mixed Methods Research, 12*(1), 1-28. doi: 10.1177/1558689816633310

TEQ

Directions: *This questionnaire is designed to help me gain a better understanding of the kinds of things that engage students in chemistry. Please indicate your opinion about each of the statements below. Please do not skip any item. Your answers are confidential. THANKS FOR YOUR HELP!*

	strongly disagree	disagree	agree	strongly agree
1. During this class, I ***talk*** about the properties of matter with other students or the instructor.	1	2	3	4
2. I ***think*** about the properties of matter when I see things like people cooking, grass being cut, leaves changing color, or ice melting.	1	2	3	4
3. I ***talk*** outside of class about the properties of matter.	1	2	3	4
4. During chemistry class, I ***think*** about the properties of matter.	1	2	3	4
5. I enjoy ***talking*** about the properties of matter.	1	2	3	4
6. Outside of class, I ***think*** about the properties of matter.	1	2	3	4
7. I find myself ***thinking*** about the properties of matter in my life outside of class.	1	2	3	4
8. During chemistry lab, I ***use*** the knowledge I've learned about the properties of matter.	1	2	3	4
9. Outside of class, I ***use*** the knowledge I've learned about the properties of matter.	1	2	3	4
10. I ***use*** the stuff I've learned about the properties of matter even when I don't have to.	1	2	3	4

Appendix D

Student Written Response Reflection Questions

Guided Reflection Questions

Carefully consider the guided reflection questions listed below. Answer in as much detail you need to sufficiently answer the questions. Reflection questions are due one week following the completion of the lab. They are separate from your laboratory report. Your answers are confidential. Thank you for your time.

1. Did you learn anything during this experiment that made you think differently about the world or see things differently? If so, explain why these ideas made you see the world differently. If not, why didn't learning make you see the world differently?

2. Was learning about the ideas in this experiment interesting or exciting? In what ways? Was it more interesting or exciting than other things you learn in chemistry? If so, what was different about it? If not, why not?

3. Did you do anything differently as a result of this new learning? Did you tell anybody else about what you learned during this experiment? Did you try to learn more about any of the ideas on your own? Did you look for examples of what you learned outside of the lab? Tell me why or why not.