Coping with Challenges and Uncertainty in Scientific Research

Case Studies of Two Postdoctoral Researchers in an Epigenetics Laboratory

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Abstract

To effectively employ inquiry-based learning to enhance students’ inquiry practices and encourage them to think and act like scientists, science teachers must have a deeper understanding of the factors that influence scientific research and attitudes about scientist practice. This research contains the experience of two postdoctoral researchers in epigenetics as graduate students in a newly established epigenetics laboratory. Two in-depth interviews, two preliminary questionnaires, a record of laboratory visits, and a supervisor interview were analyzed for this qualitative research. Even though the two postdoctoral researchers have encountered various obstacles, such as a lack of resources, scientific uncertainty, and unestablished personal identity, they are effectively maturing as scientists as a result of their capacity to overcome these obstacles. This study may provide science educators and students with a better understanding of the challenges they will experience in their scientific work and strategies for overcoming those challenges.
Keywords

scientist – scientific inquiry – scientific problem solving – scientific creativity – qualitative study

1 Introduction

An emphasis on fundamental competencies to respond flexibly to environmental changes and abilities to respond to the changes has been increasingly emphasized in education for the future. As a scientific core competency, science education has increasingly focused on the scientific practice and the cultivation of scientific creativity. An emphasis in science education has often been put on students' indirect experience as scientists as a core factor for successful science inquiry education (Barab & Hay, 2001; Hsu et al., 2010; Hunter et al., 2007). By emphasizing the practice of scientific experimentation, students are expected to practice the inquiry performance of scientists (Dunbar, 1995; Latour & Woolgar, 2013). In addition, science teachers are required to promote students' scientific creativity through inquiry-based learning. The 2015 revised curriculum of Korea, which reflected this science education trend, was changed to emphasize the importance of scientific inquiry by adding a science inquiry experiment topic that all high school students were expected to master (MOE, 2015). Harwood et al. (2002) discovered that many pre-service elementary teachers struggled to conceptualize inquiry since they had never engaged in it as students. The concept of inquiry-based instruction has been around since the early 1900s, but implementing it in the classroom has proven to be a tough task for science educators (Chinn & Malhotra, 2002; Cho et al., 2008; Jeong & Lee, 2013; Jhun & Jeon, 2009; Jin & Jang, 2007; Lee & Jeong, 2016; Lim et al., 2010; Windschitl, 2004). In order to help students develop ideas about scientific inquiry and creativity, science educators should directly and indirectly participate in and comprehend the scientific exploration activities of scientists. It is crucial for students to comprehend what scientists do and what information is acknowledged by scientists and also to directly engage in activities that help them think and act like scientists so that they can experience scientific inquiry (Yeh et al., 2012).

However, Korea's educational systems still do not seem well prepared to help students to understand scientific exploration on their paths to becoming scientists and in the process of growing up from graduate students to scientists. Scientists generally use their intuition to make logical and complex decisions based on their creativity and existing knowledge (Lederman et al.,
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Scientific inquiry is not the simple process of performing basic scientific tasks. It should combine various scientific methods such as reasoning and critical thinking with scientific information (Lederman, 2006; Senler, 2015; Yang et al., 2017). Detailed descriptions of how prospective scientists face various research-related problems in their laboratories and how they handle those problems have not been well studied. A lack of related study results on these topics makes it difficult to appropriately teach and guide our students towards an understanding of the nature of science and a hope of becoming a scientist in the future. Compared to studies in K–12 science education, there have been comparatively few studies on how undergraduates, graduate students, and postdoctoral researchers become professional scientific researchers (Delamont & Atkinson, 2001; Park et al., 2017).

The majority of experiments for secondary school and college students are generally intended to yield precise rather than unexpected findings. The “real” science that graduate students should do is more complex, and they often face failure (Delamont & Atkinson; 2001). Graduate students must also be aware of and embrace the possibility of unexpected events occurring at any point during the process, from designing an experiment to interpreting the data. These situations are frequently not fully explained and documented in any curriculum or any school courses, so students must learn them by experimentation in the lab or by watching senior students. In order to finish up their degree and become a scientist, graduate students must get used to the science lab and contextual practice for conducting important and difficult tasks. They need appropriate help and guidance to do this (Gardner, 2007; Hamui & Canales, 2014).

The creativity of scientists in dealing with scientific and daily problems may appear to be logical problem-solving process in daily routine scientific environments (Hollingsworth, 2008). In general, scientists conduct research projects in situations where they face deficits in various resources and equipment, and they daily face many personal and laboratory problems that need to be solved. Such circumstances force them to express their general and scientific creativity, which we can study. They need to have good strategies to handle such limited resources, fight with various scientific uncertainties, and endure a long research processes. Like senior scientists, prospective scientists such as graduate students and postdoctoral researchers also require such scientific handling skills. Graduate students, particularly doctoral students, may face significantly more situations than tenured academics where they need to confront and are asked to devise creative solutions to such difficulties during their degree studies (Stephan, 2012; Vogel, 1999).

In this study, we used a qualitative research approach to explore what scientific research-related issues graduate students deal with on a daily basis.
in science laboratories and how they innovatively solve such issues. For our
study we invited two previous graduate students, now working as postdoctoral
researchers in the same lab in the fields of epigenetic research. Epigenetics
is a sub-discipline of genetics that studies the regulation of epigenetic gene
expression, which is the regulation of gene expression in a state where the base
sequence of DNA does not change. Various forms, such as DNA acetylation,
methylation, and phosphorylation, are known. In Korea, epigenetics began to
be studied in earnest in the late 2000s, and when the two participants started
their degree programs, they faced the normal challenges that appear in the
study of epigenetics in the early stages and the fact that they were working in a
new research laboratory. Since beginning their master’s degree program, these
two researchers have been examining the causes and the mechanisms of alter-
ation of histone proteins in the recently established laboratory. We anticipated
that graduate students would likely experience a great deal of uncertainty in
the newly established laboratory, maybe driving them to use more of their cre-
ative abilities. Additionally, because epigenetics results can be interpreted in
a variety of ways, we hypothesized that graduate students working in an epi-
genetics lab would experience greater unpredictability, including lack of previ-
ous research on their research topic, difficulty understanding the significance
of results, and concerns about finishing the course on time.

2 Literature Review

In order to determine the significance of the experiences encountered by the
two former graduate students during their scientific practice and the impli-
cations of maturing into postdoctoral researchers, for this study we briefly
describe the accepted definition of scientific creativity and the meaning of
uncertainty, which should be overcome to express creativity.

2.1 Scientific Creativity

Creativity is not only required for significant scientific discoveries, but also
plays an essential role in science education (Park, 2011). Creativity is the engine
of scientific discovery and a fundamental driver of positive change (Hennessey
& Amabile, 2010). Creativity has been defined in various ways by researchers in
relevant academic fields. However, researchers have tended to agree that the
word ‘creative’ means new (original, novel) and useful (meaningful, significant,
valuable) (Runco & Jaeger, 2012; Runco & Pritzker, 2020; Ochs, 1990). Other
researchers, such as Amabile, have emphasized that creativity is exhibited by
the interaction of various factors, such as new thinking processes, personal dispositions, and motivation (Amabile, 1983, 1997).

Scientific creativity refers to all general and specific kinds of creativity in the field of science. Park (2004) summarized the scientific creativity model (Figure 1). Park organized the cognitive aspects constituting scientific creativity into scientific thinking, scientific inquiry function, and scientific knowledge content. Sternberg (1999) emphasized that creative thinking is influenced by affective and environmental factors such as thinking style, personal characteristics, environment, and motivation, in addition to cognitive aspects such as intellectual ability and knowledge.

Hong (2003) characterized the creativity of scientists into four characteristics. First, it matures through a long period of training and research. Second, the intellectual climate and the community that inspire creativity are important. Third, the ability to combine various intellectual and material resources constitutes creativity. Finally, it comes from the intellectual dignity of being sufficiently familiar with existing methodologies, theories, and interpretations while at the same time not being overwhelmed by them. Such characteristics are generally found in the daily research processes of most scientists, certainly including well-known genius scientists such as Einstein and Newton. Nevertheless, to the general public and prospective scientists, the creativity of scientists is often misunderstood as brilliant ideas and brilliant problem-solving results. Research on creativity at the individual level has also unfortunately focused on geniuses with extraordinary abilities and factors that

![Figure 1: Scientific Creativity Model (MSC), adapted from Park (2004)](image-url)
characterize creativity. For example, studies on creative genius have tended to emphasize problem-solving ability (Garrett, 1987; Treffinger, 1995; Brophy, 1998; DeHaan, 2009) and sensitivity to problem discovery (Csikszentmihalyi, 1999; Getzels & Csikszentmihalyi, 1976). Even so, exploratory research on the creativity of scientists using the history of science have also focused on famous scientists such as Einstein and Edison (Song, 2013).

Peter Medawar (1984), a biologist who won the Nobel Prize, once referred to scientific research as “solubility technology.” In real research situations, scientific practice faces many complex issues and problems. According to Medawar, the skill of being a scientist generally includes continuing to reimagine the big problems, breaking them down into smaller, more solvable parts (i.e., solubility), and guessing which of these small parts will be the key to solving the whole topic. In other words, scientists must envision various observable outcomes in many different ways and set up the research designs that help formulate different hypotheses. These processes must be performed using logical and analytical approaches. Experts who have studied creativity have found that complex logical thinking is always a part of the creative process in many research fields, especially in scientific fields. (Hollingsworth, 2008; Tardif & Sternberg, 1988). Taken together, the entire process of scientists’ hypothesizing, conducting experiments, interpreting results, and proving theories on research topics might require various kinds of scientific creativity. In addition, Hollingsworth (2007) described high cognitive complexity as “the ability to understand and observe relationships among complex phenomena in new ways, to see relationships among disparate knowledge” (p. 129). And they argue that a key indicator of the high cognitive complexity of scientists is the level of cognitively internalized scientific diversity. To paraphrase his argument, the prerequisite for scientists to make major discoveries needs a high level of cognitive complexity.

2.2 Overcoming Uncertainty as Obstacles of Creativity
As the study of creativity has developed, extensive research has been done on the elements that either hinder or foster creative expression. Evans (1991) noted that everyone will face internal and external obstacles in the creative process. Wolpert (1996) stated that scientific creativity is always limited by internal inconsistency in emotion, uncertain nature of scientific studies, and existing bias about knowledge.

Positive stimulation of scientific creativity not only promotes creative thinking but also improves the factors that slow down creativity. The expression of scientific creativity can be observed in the complex relationships between various organizational and environmental factors that stimulate a scientist’s
intrinsic motivation. Most scholars have categorized and organized such factors affecting the expression of creativity into internal, cultural, and environmental factors (Adams, 1986; Amabile, 1983; Evans, 1991; Lee et al., 2017; Von Oech, 1983; Yoon, 1994). Adams (1986) classified hindering factors for creativity into four categories: perceptual disabilities, emotional disabilities, cultural and environmental disabilities, and intellectual and expressive disabilities. In a short summary, there are various internal and external factors influencing the expression of scientists’ creativity, and it is important to remove such factors that interfere with creativity or adopt ways that facilitate creativity processes to successfully handle scientific obstacles and problems.

Uncertainty has been identified as a potential driving force for the biases against creativity. When people feel uncertainty, they may experience a more negative association with creativity, resulting in a lower expression of creative ideas (Mueller et al., 2012). Uncertainty also appears in situations where the future is unpredictable. They also feel uncertainty when there is not enough information while critically evaluating data or predicting results (Gifford et al., 1979). Therefore, individuals are generally motivated to avoid uncertain situations (Whitson & Galinsky, 2008). Uncertainty also leads to low social relationships and prejudice against creativity.

Amabile (1996) asserted that the more original the idea, the more uncertain it is. In addition, while advocating for a new idea, people may experience failure, social rejection, and uncertainty about the completion of an idea. Thus, uncertainty is a kind of negative view of creativity or an implicit view of creativity (Lee et al., 2017; Nemeth, 1986). This can lead to prejudice. Lee et al. (2017) demonstrated that if participants experienced fear and ambiguity, they exhibited implicit negative biases against creativity. Considering the critical role of uncertainty in the expression of scientific creativity, organizations and managers should not only help colleagues to successfully handle such uncertainty but also encourage them to have positive attitudes toward creative ideas in the workplace (Lee et al., 2017).

3 Research Questions

The goal of this study is to examine how two postdoctoral researchers who recently received their degrees used their general and creative scientific skills while dealing with numerous personal and research-related problems while working on a project during the course of their degree studies. It may also be possible to pinpoint the elements that helped them get overcome these challenges and eventually become scientists. Our results could be helpful for
science inquiry education and aid science educators, especially in higher education, to better understand scientific research and the work of scientists.

The specific research questions of this study are as follows.

1. What challenges did the two study participants encounter and how did they overcome them as young epigenetics researchers?
2. How does the creativity of scientists emerge in various circumstances, and how does this process influence their identity as scientists?

4  Methods

4.1  Participants
To explore our study questions, we invited two postdoctoral researchers who had recently completed doctoral degrees in the same laboratory as study participants. The two participants, Choi and Lee (pseudonyms), had been working in the epigenetics laboratory since starting their master’s programs, while conducting challenging research to find the factors that cause changes in invisible histone proteins.

The research background of the two participants is as follows.

Choi had been using yeast as a research cell model to study the effects of chromatin regulators and histone translation on gene expression. Choi started as an undergraduate student in the same laboratory and completed her doctoral course, and in this process, she took charge of the laboratory work for about 5 years. At the time of the study, she was working as a postdoctoral researcher in the same laboratory.

Lee was studying how chromatin regulators are involved in gene expression changes in Candida albicans, an opportunistic infection, to recognize changes in the external environment to form mycelia and acquire pathogenicity. Lee took master’s and doctorate integration courses in the same lab as Choi and at the time of the study was working as a postdoctoral researcher in the same lab.

4.2  Data Collection
We collected raw data for this study over 6 months, from February to July 2021, using two pre-questionnaires and two in-depth interviews. Also, background data on the features of the participants’ laboratory, relationships among its members, and research projects were collected from all members of the
laboratory using the first open-ended questionnaire. Before conducting in-depth interviews, we conducted preliminary interviews with the advisor over the course of two visits to gather information on the characteristics of the laboratory study and the participants, and then we formulated the interview questions.

We provided the participants with a questionnaire and enough time to reflect on their past experiences as graduate students and reply to the questionnaire before the in-depth interview in the laboratory. Instead of fragmentary pieces of recollection, the participants were asked to describe their experience as graduate students in detail, from the master’s program period through the current time period. Using two preliminary surveys and two semi-structured questions, we conducted in-depth interviews with the two participants. Each in-depth interview lasted around 90 minutes.

The direction of the interviews was carefully planned to consider the experiences they had presented, and a semi-structured questionnaire was created for effective interviews. The participants were asked to freely talk about their experiences from graduate school to the present during the first in-depth interview. After the first interview, we determined and listed the obstacles and research-related problems they faced and generated interview questions (shown in Table 1) for the second visit. During the second interview, we asked how they faced and resolved such major problems one by one until we fully understood their solutions to the problems. In addition, we collected additional data through e-mails, text messages, and phone calls with them after the second interview until our understanding of each topic was fully satisfied.

### Table 1: Examples of questions used in the interviews

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<th>Round</th>
<th>Questions</th>
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<tbody>
<tr>
<td>First</td>
<td><em>Questions for the understanding of graduate life and research as a whole</em>&lt;br&gt;– Please introduce the topic you are researching.&lt;br&gt;– What motivated you to continue your doctoral program after completing your master’s degree?&lt;br&gt;– Have you ever wanted to stop studying or researching? If so, what was the reason?&lt;br&gt;– What do you think was the key to continuing your research?&lt;br&gt;– What do you think is the biggest difference between being in a degree program and now being a researcher?</td>
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4.3 Data Analysis

Laboratory observation notes, interview data with the advisor, questionnaire responses, and the two participants’ dissertations and publications published in academic journals were reviewed alongside in-depth interview data to strengthen the study’s validity. We did open coding while listening to the in-depth interviews again. In particular, we aimed to address the participants’ experiences and realities of life through the process of capturing live passages that revealed their inner selves and elaborating on their meanings. For microdata analysis, the entire audio recordings of the in-depth interviews were listened to, vivid quotes were chosen, and the nuances, tones, and sections emphasizing the voice’s speed were repeatedly listened to. In particular, we focused our attention on the actuality of the attitudes, emotional states, and thinking patterns that the two participants experienced during their encounters (Witz, 2006). We used this strategy with great care, with the aim of accurately evoking the message contained in the in-depth interview data and conveying it to the reader.

Several methods were additionally applied to improve the validity and reliability of data analysis. Peer debriefing was employed to increase the accuracy of the descriptions. A non-participant peer reporter was assigned to provide an empathetic description and checked the correctness of the interpretation. Confirming the content that was not clear or was questionable in the analysis

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TABLE 1 Examples of questions used in the interviews (cont.)

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<th>Round</th>
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<td>Second</td>
<td>Problems encountered in research situations and how to overcome them</td>
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<td></td>
<td>– Have you ever experienced a causal complexity that made it difficult to determine the cause and effect during an experiment?</td>
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<td>– Have you ever experienced that the experimental situation that could not be repeated because the test material was very sensitive?</td>
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<td>– Have you ever had the experience of not giving up on an experiment and getting results after proceeding?</td>
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<td>– When conducting a study, have you ever stopped or abandoned the experiment due to practical problems that occurred that caused it to go differently than you had initially thought?</td>
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<td>– Have you had the experience of constantly making judgments and proceeding in unclear situations?</td>
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<td></td>
<td>– Please tell us if you have ever sought help in a difficult experimental situation.</td>
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Second Round Questions

1. Have you ever experienced a causal complexity that made it difficult to determine the cause and effect during an experiment?
2. Have you ever experienced that the experimental situation that could not be repeated because the test material was very sensitive?
3. Have you ever had the experience of not giving up on an experiment and getting results after proceeding?
4. When conducting a study, have you ever stopped or abandoned the experiment due to practical problems that occurred that caused it to go differently than you had initially thought?
5. Have you had the experience of constantly making judgments and proceeding in unclear situations?
6. Please tell us if you have ever sought help in a difficult experimental situation.
process was directly done with the participants. In addition, we shared and discussed the topics with the study participants so that we would not arbitrarily analyze and interpret them in the analysis process.

After extracting important paragraphs from the transcription data, the participants' difficulties and scientific-related issues were recognized and arranged along the timeframe of their degree programs. In order to adequately investigate the multidimensional relationship between the subjects, the experienced challenges were grouped in chronological order. We also determined how two people overcame these obstacles and assessed whether or not these solutions were associated to creativity. Lack of funding, ambiguity in scientific research, and the quest for identity were all major roadblocks for them. Finally, based on their experiences and accomplishments, we examined the elements that shaped their identity of self as scientists.

5 Findings

Based on our in-depth interviews, we found and subdivided the scientific research-related problems the two graduate students faced into three categories: resource deficiency, scientific uncertainty, and personal identity problems. For each problem, we explored and found how the two graduate students handled the problems using their scientific creativity during the process.

Specifically, we first described how the two graduate students dealt with a scarcity of resources. They successfully overcame a scarcity of human, literature, and financial resources by applying various creative skills to their scientific endeavor. Following that, we described their struggle and coping with scientific uncertainties. To remove the uncertainty, they gained a better understanding of scientific uncertainty, refined the scientific inquiry process, and enhanced scientific thinking. Finally, we presented how they managed their emotional problems and developed their identities as future scientists. We described how they overcame the experimental failure and established their identities as scientists through strong interactions with their advisor and teammates. Details on each subject follow.

5.1 Handling of Resource Deficiencies

What we found was a lack of resources in the new lab.

The two participants, who started a long degree program on a new research topic in a new laboratory, were first faced with a lack of various resources. Under the guidance of a newly appointed advisor and in a newly constructed
laboratory environment, the two participants began their master's degree program. Their research topics were in epigenetics, which was a relatively new research area at that time in Korea. Such an environment forced them to face a lack of references and human and material resources both in the laboratory and the national level. Both the master's students and their advisor started as pioneer researchers in the epigenetic study field in Korea. According to the participants, the absence of senior lab members who could give answers to their questions pertaining to the research was the biggest obstacle for them at an early stage of their studies. They relied only on the guidance of the advisor to resolve such questions and problems, and they had to learn how to properly conduct experiments on their own in many situations. Participants described such situations as follows:

Choi: During our first experiment, we did not have any senior researchers in the lab who could address many of our questions. So there was no answer, and I was frustrated. At that time, I learned a lot of experimentation methods by looking on BRIC [the Biological Research Information Center, an online biological information cluster and discussion forum in Korea] and troubleshooting using various protocol books to go over every step of the experiment, which appears so easy and simple now.

Lee: I had never previously studied NGS [next-generation sequencing] before starting in the lab, so I relied solely on the materials provided by my professor. I wasn't sure if this was correct. The sequencing library is now easily prepared, but I was nervous and concerned at first. “Did I do it correctly?” and “Did the results come out correctly?” were two concerns I had at the time.

To successfully conduct scientific projects, laboratories, apparatuses, and equipment for the experiments are necessary, and relevant experimental methods should also be employed. Our participants also had to acquire basic knowledge of epigenetics and needed to understand the experimental materials to be used in the experiment. They, along with their advisor, searched for the various resources they needed and studied how to collect the relevant resources and how to appropriately use them in the experiments. They faced and creatively overcame the scarcity of human resources, academic reference materials, and lack of both the necessary skills to conduct experiments and supplementary resources in the following ways.
5.1.1 Human Resources
To resolve a deficiency in human resources, such as a lack of senior researchers, the advisor helped the participants to have interactions with graduate students and researchers in other laboratories. In other words, they compensated for a shortage of personnel resources by communicating and working together with other institutions’ research laboratories. These creative activities not only helped them overcome the human resources shortfall in the new laboratory, but also helped them realize the experimental mistakes that could not be identified previously.

Additionally, participants reported that their advisor encouraged them to attend various academic conferences and facilitated their discussions about their experimental methods and results with teammates and others. They recalled that such opportunities and activities broadened their knowledge of the study topic and appropriately compensated for the lack of senior human resources in the laboratory.

Lee: My professor took us to conferences every chance she had since we started our master’s degree. My advisor took us to give us the chance to meet with various scientific researchers even though we had no results to share at the conferences. By attending conferences and encountering various research methods and themes, I learned a lot about how to apply them to our research.

Choi: We collaborated on work with a lab similar to ours that investigated histone protein from a different perspective using a research process similar to ours. They compensated for the lack of people in our lab who could discuss the research since they could provide a variety of perspectives on the modification of histone protein.

To resolve the deficiency in human resources, the two participants in the end understood the importance of colleagues working together to solve the problems. In the process, the advisor helped them develop research cooperation with other graduate students and other research groups.

5.1.2 Literature Resources
Because epigenetics was a new study field in Korea when the participants began their degree programs, finding appropriate references was difficult. Every week, they and their advisor searched for, located, read, and assessed
papers published in international journals. The journal club, which met every week to review publications, was still active in their laboratory at the time of the study. The journal club evolved into a kind of lab culture that helped fresh graduate students rapidly understand their research fields. Even when directly related papers were not found, the participants read through relevant papers and tried to apply the results to their studies.

Lee: At that time, there were only three master’s students, so we had to present a journal review every week. I read and reviewed journals once a week. I must have read most of the published papers in my study area. Later, even when the journal club was on a day-off, I asked the professor if I could personally read a paper during the week and do a mini-journal club with her.

Choi: It was difficult to find literature on the factors that modify the yeast histone protein, which is the cell model system I studied. Naturally, no article addressed this precisely, so I looked for as many study materials as I could that were even tangentially related. So, I spent a lot of time talking with the professor about how they might be related. Until we have sufficient evidence to support a hypothesis, we want to investigate it.

The two participants experienced a lack of research data on the factors affecting the histone deformation in the research cell model. At the beginning of their degrees, graduate students often face unfamiliar academic theories and research methods. The two participants gathered data that might have a small connection to solving their problem and logically discovered the connection by drawing a conceptual diagram. Additionally, to overcome the deficiency in reference resources, the advisor and participants together put their efforts into finding appropriate and relevant papers in international journals. Through journal club, they fully studied the papers, which were difficult to obtain, and talked about methods and results with each other, helping them to fully apply those results in their coming experiments. Contemplating and attempting to resolve a shortage of reference resources might be viewed as the beginning of the manifestation of subjectivity in early researchers influenced by epigenetics. It helps to foster a sense of responsibility for research and to cultivate the characteristics of a scientific researcher.

5.1.3 Financial and Supplementary Resources
Research funds are required to acquire supplies and laboratory items for research. They are an essential component in maintaining a laboratory. The
participants needed laboratory instruments to cultivate the cell for their research in the laboratory and needed research funding to do genetic extraction and analysis. The burden of obtaining these research funds was inevitable for the two participants, including the advisor. Failures of experiments forced them to throw away expensive reagents and they became worried about the expenses pertaining to gene extraction for experiments. These concerns were likely to have negative impact on the researchers' creative thoughts. To solve this problem, they put in a lot of effort and finally secured laboratory-level research funds and procured scholarships for each graduate student. Consequently, reducing the burden of a lack of research funds influenced not only the procurement of materials but also participants' confidence and motivation.

Lee: As I enrolled in the master's degree program, the scholarship helped me tremendously, and I could pay my tuition fees, procure research materials, and manage my living expenses. To be honest, I was barely able to go to college with the help of student loans. Entering the graduate program was a big financial burden for me, but thanks to the fellowship that covered 5 years, I was able to pursue my studies and research in graduate courses without any financial constraints.

Choi: I lost some driving force for research after finishing my doctoral degree till I received my postdoctoral research funds. With my research money, I will be able to continue my career as a postdoctoral researcher and study for another 3 years without having to worry about research material costs. I also realized how my research is important and worthwhile to society. Especially because I got the fund under my name, I felt a kind of duty to successfully perform the research.

While Lee obtained a scholarship early in her degree, relieving the pressure of long-term study and allowing her to work on a degree with great confidence, Choi also earned research grants after her doctoral degree. Prior to formulating the research questions, it was important to gain background knowledge on the topic of study and select relevant research methods, experimental techniques, and ways of handling the experimental materials. Scientists have often had to deal with the problem of a lack of resources from the beginning of the research. Choi's and Lee's successful funding helped them move forward in their experiments by removing the deficiency of financial and supplementary resources in the laboratory. Both participants were able to get the items and materials required for their investigations, while starting up the new projects in a new laboratory with their professor.
5.2 Dealing of Scientific Uncertainty

What we needed was the magic school bus.¹

Scientists identify research problems, formulate hypotheses, and conduct experiments to find answers to the problems. In a science experiment, the expected results may or may not be obtained. Our participants repeated experiments to confirm their results and sometimes modified a hypothesis if it was wrong. The two graduate students wanted to uncover a component that affects histone protein modification and, as a result, gene transcription. At the beginning of the study, targeted or related factors were not known at all. So it was difficult to find relevant references for their study. Where should they start their experiments? The two participants faced great uncertainty on their projects, but needed to overcome such uncertainty. To understand the nature of uncertainty and reduce such uncertainty in their experiments, they first increased time efficiency by enhancing the technology and sophistication of the experiments and attempted to make logical and rational decisions, as far as possible, in unclear situations. The followings show Choi’s feelings on her research’s uncertainty and several issues at the time.

Choi: We were looking for the factors associated to histone protein alteration that influence gene transcription. The things we’re looking into should exist, but nobody had discovered them yet; nobody. Because we couldn’t see them with our eyes, I’m saying we needed a magic school bus. I hoped to get on the magic bus and directly get into the cell to find answers. Because it was so frustrating for me.

To successfully conduct experiments and manage projects in science, facing and overcoming scientific uncertainty is critical. We will describe how the two participants overcame their scientific uncertainty in three different ways: gaining a better understanding of scientific uncertainty, refining the scientific inquiry and experimental process, and improving scientific thinking.

5.2.1 Understanding Scientific Uncertainty

In experimental situations, the experimental systems used by our participants at each stage were very sensitive. For example, even if they were previously

¹ The Magic School Bus is a popular young children’s book series written by Joanna Cole that tell the adventures of a science teacher and her students who take field trips using a school bus with magical abilities to explore different science-related phenomena, such as, traveling inside the human body (see, for example, Cole, 1990).
successful, they could not reproduce experimental materials for genetic modification again under the same conditions on the next day. In addition, in some cases, certain factors that had not been identified in previous studies were found to affect the results in subsequent studies. These kinds of phenomena are called scientific uncertainty. Scientific uncertainty often makes graduate students become frustrated with their experiments and in severe cases causes them to become disappointed and quit their overall studies. To overcome such uncertainty, they need to face scientific uncertainty and understand that it is always possible.

Lee: We know that the results of experiments can sometimes vary from person to person. When we plan an experiment, if there is an experiment where temperature control is important, we expect good results if we do the process well. However, this is often not the case in reality. For example, even if we add all the nutrients needed by the medium for growing, they are made differently depending on the weather of day we make them. Therefore, to solve this uncertainty problem, I have to admit that there is such uncertainty in my experiments. To reduce the uncertainty, for some experiments, I tried to finish all processes of the experiments within a day by working the full day.

Choi: When unexpected results occur, I think and say, “That’s possible.” We believe that we will hypothesize and obtain the result we want, but sometimes we do not know real nature of the result. I think that is the nature of epigenetics. From the time we hypothesized, we may have been wrong, we may have used the model incorrectly, or the experimental method may have been wrong. We should and could first understand and accept the uncertain nature of scientific research.

In different ways, the two participants came to accept the uncertain nature of scientific research, especially in epigenetics. Lee had trouble producing Candida bacteria, while Choi could not extract a specific gene from a yeast culture in a master’s course. These issues suddenly resolved themselves without it being clear what the precise solution had been. For example, for two years, Choi attempted and failed to extract genes from a strain of yeast being studied in her lab. At the end of her master’s degree, Choi attempted the task again. She used the same method to extract genes from the same strain of yeast, but this time it worked. Similarly, Lee had unexpected success after 6 months of failure to grow Candida in liquid media. While neither students could explain why their challenges were suddenly resolved, they both came to the realization that these problems could just as easily reappear later during their research.
Understanding and accepting unseen solutions to problems led students to have less frustration when attempting to solve difficult problems.

5.2.2 Refine Experimental Process
The “failures” that graduate students most often experience are known as “technical” tasks, such as setting up experimental equipment, culture preparation, protein separation, and purification. The two participants quickly recognized their lack of laboratory experience and their ability to prepare for experiments. They realized that knowing basic techniques and skills is critical to successfully conducting a study.

Although we cannot exactly describe how graduate students learn various experimental techniques, such tacit knowledge of techniques can be acquired if the experimental preparations and processes repeat and continue in the laboratory. Usually, tacit knowledge is naturally and often unintentionally passed down from senior to junior members in the laboratory. Nevertheless, daily hard practice can help further refine experimental techniques and overall experimental processes. Our participants recalled that due to their efforts to materialize and shorten the technical work for experiments during their early graduate school period, they were then able to fully focus on given research issues.

Lee: Now, I successfully developed a predictive hypothesis about the effects of histone protein on gene expression, and determined whether there were any interactive factors through related papers. I’m starting to believe that even if I can’t locate proper references that can tell me the actual results, I’ll be able to figure it out using some other ways. So, whenever I find something in my research that could be useful, I organize it and save it for my research.

Choi: There was not much change in the model or method of research. However, over the past 10 years, my experimental techniques have significantly improved. Therefore, it takes much less time and I have become more accurate when preparing materials to make a medium for a culture or to conduct PCR. Therefore, I can save the time needed for the experiment and use that time to solve and study the remaining problems in my research.

Lee had mastered the technical skills needed for the lab at the beginning of her degree course, while Choi chose to increase the sophistication required at this stage of the research process. Both our participants dealt with histone proteins, but there are different research techniques that come from the differences and
characteristics of yeasts and *Candida albicans* used to conduct experiments. Learning the technical skills required for experiments and broadening their knowledge were critical to conducting experiments effectively and growing as scientists. It will take a great deal of practice to identify and develop the technical skills and scientific abilities they need on their own and become experts. Hard and refining practice should be considered a solid foundation for their successful research.

### 5.2.3 Improving Scientific Thinking

Park (2004) emphasized the importance of “non-habitual thinking” in the field of divergent thinking, suggesting that scientists should be aware of and try to mitigate cognitive biases caused by habitual thinking. In uncertain situations, people are prone to show cognitive biases when making decisions based on chance or using ad hoc procedures. During scientific study, unanticipated results or events often lead to biased reasoning. This kind of cognitive bias can lead scientists to rash conclusions and create interpretation problems. So, to handle scientific bias well, scientists should improve their scientific thinking, which will effectively reduce or remove bias in their reasoning. Our participants, to overcome such potential bias, actively interacted with research colleagues in their own and other laboratories.

When the participants encountered uncertainty in the results’ reliability due to unknown mechanisms, they adopted a clever way through scientific thinking. To ensure that they were not misinterpreting results or were not misconducting experiments, laboratory colleagues exactly repeated the same experiments using the same manual. If the same results were produced from the second experiment, they could more easily assure their results by eliminating uncertainty and cognitive bias. If not, they could still consider their original results in different ways to remove bias or uncertainty. Scientists must cope with uncertainty and cognitive bias to successfully conduct experiments, even when the experiment repeatedly fails.

**Choi:** I keep doing this experiment routinely, but sometimes I may not pay attention. For example, it is like you thought you had added salt while cooking, but you did not. Such incidents can happen with any person working in a laboratory. If the results were different from what was expected, the same experiment was executed with other members to know what the problems were with the results. Even so, some experiments were conducted by all members of the laboratory taking turns.

**Lee:** *Candida albicans* forms mycelia, which appear well in a liquid medium; however, when we used a solid medium in the same conditions,
the mycelia did not form. My professor asked, “Why isn’t it possible? Try again.” We tried this many times, but it still did not appear. So, I thought the procedure might not be a problem and there might be another reason. So, I talked with a doctoral student in another laboratory who was collaborating with us on the research. She confirmed that no mycelia would be formed in the solid media, unlike in the liquid medium. Through this process, we could remove the uncertainty.

Whenever the participants had a learning experience related to uncertainty or scientific bias, they structured it and shared it with the rest of the lab members during lab seminars or meetings. Through in-depth discussion, they learned from their failures and often came up with better solutions. Such problems and solutions were documented and later shared with junior members. To counteract cognitively biased thinking, the participants used interactions with their advisor, lab members, and colleagues in other laboratories. Through human interactions, they were able to reduce premature conclusions and further focus on the given problem being solved.

5.3 Establishing Personal Identity as a Scientist

It was like running a marathon. It was a battle against the constant desire to give up.

During 10 years of graduate student life, persistent failures in experiments and uncertainty about the future had great emotional effects on our participants in various forms. Consequently, their graduation got delayed, they become hesitant and wandered from their master’s course to moving forward to their PhD, or even failed to proceed with an experiment. Scientists experience countless failures as they prepare for and conduct experiments. This experience of failure can elicit emotional reactions and behavioral changes.

Lee: I’ve spent the last 10 years here. I was very concerned about the final semester of my doctoral program. At the time, my main concerns were, “Will I be able to live as a scientist if I get my doctorate?” and “I don’t think my thesis is finished yet; can I successfully graduate?” The professor pushed me to hurry up and graduate, but I postponed my graduation by one semester since I was very concerned about my future.

Choi: As the studies in our laboratory are based on fundamental science, it generally takes a long time period to finish up experiments and
complete a thesis. In an applied science laboratory, functional proteins were analyzed, and the results of the analyses were easily summarized as the thesis. We invested a lot of time, energy, money, and human resources to reveal the mechanism that affects the deformation of histone proteins.

The scientists were continually confronted with unpleasant emotions, which harmed their ability to think scientifically. Negative emotional states not only undermine creativity but could also lead to pessimism in everyday thinking. Negative emotions sometimes lead to frustration about hasty conclusions or failures rather than encouraging new ideas or scientific solutions for research. Through in-depth interviews, we found three important factors that helped the participants successfully tackle such uncertainty and establish their personal identities as scientists: developing a positive relationship with their advisor, improving their failure tolerance, and pursuing self-recognition and self-evaluation.

5.3.1 Relationship with Supervisor
Strong interaction between environmental and personal factors is important for the expression of individual creativity. The two participants completed their degree programs in the same laboratory for approximately 10 years and continued their research as postdoctoral researchers. After completing her PhD, Lee was terrified of becoming an independent scientist, while Choi was afraid of repeating the experiment failures that tormented her during her master’s program. They both experienced delayed graduation and made the difficult decision to continue pursuing their higher degrees. However, in the end they both successfully overcame their hard times by closely sharing their difficulties with their advisor, which led them to feel a sense of belonging to the laboratory and scientific community.

The first reason why they were able to withstand many experimental failures and overcome worrying about their future for such a long time was close interaction with their advisor. They shared the research process and experimental results in great detail with their advisor. The advisor, also as a senior researcher, gave positive and negative feedback fully focusing on the given problems, and also sincerely trying to understand their emotional anxiety about the experiments and their future. Positive feedback from the advisor boosted the participants’ confidence and facilitated divergent thinking, while negative feedback allowed them to reflect on their research process and refocus on given problems. Through these interactions, they could significantly reduce the fatigue brought on by long study periods and remove the temptation to stop their studies and lighten the burden of negative experimental results.
Lee: If I had not met the professor, I would not have started the PhD program after completing my master's degree. The professor's influence has been great on me, as I still continue to study in her laboratory after completing my PhD. Even though there were some times when my professor treated me harshly in trying to guide me to do well, I didn't get upset because I knew she was doing it with the hope that I would do well.

Choi: There were three research topics that I had to complete to graduate, and I could not get consistently successful results on one of them, so I felt greatly depressed. At that time, my professor allowed me to move on to another one. I felt that the professor understood what difficulties I was encountering and helped me to keep up my degree studies.

5.3.2 Improving Failure Tolerance
When the two participants started their graduate program, they were not very successful in their experiments, and it made them feel greatly frustrated. They did not experience such failures when they were undergraduates. Until the day they completed their projects and received their degrees, they continued to experience many different types of failures. They put a lot of effort into overcoming and resolving such failures within a scientific framework. One thing that helped them not surrender to the failures was improving failure tolerance.

Lee: The main aim of my research was to discover the role of Me₃, one of the factors in the genes that were originally produced under mycelial induction circumstances. I won a scholarship to work on this. Unfortunately, I couldn't identify this factor for a long time. I was quite frustrated. Nevertheless, I thought over the problems and searched for any relevant data to overcome them with the professor. I would have felt too hopeless if I had thought about it alone. I was able to check with and get advice from my professor whenever I discovered any useful data or information. Based on that, I changed my hypothesis from the incorrect one and in the end was able to complete the research.

Choi: Even if the results of an experiment were not good, I usually organized them as if I were preparing for a formal presentation. When I prepared for a conference presentation, I prepared answers to questions about what other people would ask about the results. As I had to respond to the questions, I organized my thoughts and mentally went over the results. It gave me further understanding of my results, regardless of their success.
The two participants tried to quickly manage negative emotions about their failures rather than thinking negatively about them over and over. Through active interactions with both the adviser and other lab members, Lee employed a variety of ways to identify and actively correct the variables that contributed to the experiment’s failure. Choi, on the other hand, had a strategy of first dividing, organizing, and logically analyzing all research phases and then discussing each topic with the adviser. The process of gathering additional data and thoroughly examining the experimental method in order to pinpoint the problems enhanced their positive attitudes to the failures. That is, their efforts and cooperation with the advisor and lab colleagues developed their resilience to failure, and it allowed them to express scientific creativity in their experiments. In other words, improving failure tolerance helped them become successful scientists.

5.3.3 Standing as an Independent Scientist
The belief that a person’s activities are meaningful and valuable functions as the power that enables them to overcome difficult processes and continue their activities. The two participants believed that their research would be beneficial to society because it verifies the process of epigenetic phenomena. Given that many types of cancer are caused epigenetically in the process of gene expression rather than gene modifications, Lee and Choi believed that their research could provide basic data to help determine the causes of many different cancers. Establishing a personal identity as a scientist can help scientists express their creativity and successfully conduct research.

Lee: When I go to a conference to make a presentation, many other scientists are interested in my research results. In my study, I used *Candida* bacteria as a culturing model system, unlike others. Yeast is a good system for studying gene expression and certain transcriptional regulatory mechanisms, but its phenotype is too simple to evaluate gene expression. However, *Candida* bacteria have various phenotypes, although their transcriptional mechanisms are not known much yet. Other scientists have shown a lot of interest, which means that I could know our system is worth studying.

Choi: Being in charge of the laboratory for the last 5 years, I had to take care of all the miscellaneous work needed for the lab. It was difficult to manage juniors and handle administrative work. The hardest thing was that I could not focus on my research at that time. As the oldest senior now in our lab, I happily accept my responsibility to help my juniors and
ensure that the lab is properly running. Now I have well established my identity in the lab as a postdoctoral researcher.

Positive feedback from senior scientists in the research field helped the two participants strengthen their motivation and inner sense of achievement through the belief that their research was meaningful. Even when it was difficult to achieve success in an experiment, they considered the situation a type of driving force to achieve overall research goals. Now, as postdoctoral researchers, they fully understand their responsibility for junior lab members, which includes coaching and helping them.

Establishing their identities as scientists has consistently played a role in helping them express their scientific creativity and overcome many environmental challenges. At the early stage, our participants overcame material problems, and in the middle stage they elaborated their experimental skills and developed independent decisions on the experiments. Finally, thinking of themselves as scientists and focusing on scientific thinking helped them to control many other external and internal obstacles.

6 Conclusion and Discussion

Scientists have to conduct scientific problem solving and complex logical thinking in all of the processes of planning research and conducting experiments. Our investigation of two current postdoctoral researchers in epigenetics led us to the conclusion that each of their research processes might be viewed as a manifestation of scientific creativity. As graduate students, they confronted several internal and external challenges and issues that they overcame one by one during each stage of the research process before finally becoming accomplished scientists. We will discuss three aspects of their activities. To solve problems in scientific practice, we will talk about the role of human agency as a driving force, the management of uncertainty as an orientation force, and the regulation of emotions as a modulating force.

6.1 The Driving Force: Human Agency

According to Pickering’s (1995) argument, the nature of epigenetics, which our participants have dealt with, needs both academic and material agency that affects the researchers themselves. Academic agency can be achieved if one works according to the culture of a specific academic field. Our young participants told us about the differences between their and others’ research theories
that explain the functional processes of histone proteins in epigenetics. They embraced the characteristics of epigenetics and advanced their findings to make themselves more developed and experienced in the academic field.

Our participants altered their goals, implementations, and interests to fit the situations based on their strong willingness to do so when original plans were not achieved and intended reactions did not occur as planned. They realized that the targeted proteins and surrounding elements on which they worked were intertwined, affected each other, and also depended on their experimental execution. This means that academic and material agencies affect each other, and the participants realized such aspects and successfully resolved their problems using human agency. In the process, we also found that language that appears in the process of constructing knowledge, discovered by scientists, is an important component of the material world (Manz, 2015; Pickering, 1995; Roth, 1999; Roth & Lawless, 2002).

As the two participants developed their identities as scientists, they each decided on their direction and acted accordingly, understanding their research goals and their roles in the process. That is, human agency drove them to conduct research and forced them to solve scientific problems on their own. They realized their roles in the laboratory and implemented those roles throughout the research processes by working together closely with other laboratory members. After struggling through overcoming various laboratory situations during their graduate courses, our participants became senior researchers in the laboratory when they became postdoctoral researchers and were able to successfully establish the culture of the laboratory as well as their identity as scientists.

6.2 Orientation Force: Uncertainty Management

Scientists typically generate initial research ideas and subsequently develop hypotheses to investigate through abductive thinking processes (Peirce, 1955). The process of establishing scientifically creative hypotheses and designing research generally includes great uncertainty. The level of uncertainty scientists feel and how they feel about the uncertainty can have a large effect on facilitating or hindering the successful initiation of scientific inquiry. Our participants also had to set the direction of their study through facing, understanding, and accepting scientific uncertainty.

According to Delamont and Atkinson (2001), many graduate students often have difficulties on the nature of “experiment” itself, such as preparation of experimental equipment and materials rather than executing a meaningful experiment. At the early stages of their degree programs, our two participants...
also often failed to prepare materials for experiments for 2 months in one case and 6 months in the other. Successful preparation of experimental materials and acquisition of technical proficiency after resolving these problems using scientific creativity helped them to develop overall confidence in their experimental executions and also facilitate problem-solving processes. Their various opinions about and perspectives on the projects, which came from their confidence, brought them deeper understanding and helped them effectively face the uncertain nature of the scientific experiment. In particular, exploring reasons behind the failures of experiments, seeking experimental advice from others, expanding the scope of their studies, and developing divergent thinking helped them overcome the uncertain nature of the experiments themselves.

During their studies, our participants also had to face and overcome the uncertain nature of the epigenetics research field. They worked on uncovering the causal relationship between histone proteins and several factors that regulate the transcriptional phase. As with most subjects in epigenetics, both the research model and related factors in their studies were invisible and very sensitive, making it difficult to predict the pattern of change. In other words, they constantly faced situations where they had to deal with uncertainty and make difficult cognitive decisions. Through literature studies, they worked on understanding the uncertain nature of the interactions between invisible proteins and the surrounding environmental factors. Also, they repeated their experiments to reduce possible process problems even for minimal discovery and obtaining of data, which in the end helped them reduce the uncertainty. In addition, they attempted to manage the negative emotions associated with uncertainty by examining and solving research-related problems in a group. Even while accepting unexpected results and trying to find their causes, they developed their scientific creativity. Successfully managing various uncertainties oriented them to further deeper research projects and more effective conducting of experiments.

6.3 Modulation Force: Emotional Regulation
Successful emotional regulation is also important to continuously express daily scientific creativity while becoming a scientist. Intrinsic motivation, cognitive processes, knowledge, and self-efficacy have been identified as influencing factors on creativity expression (Amabile, 1997; Simonton, 2012, 2000; Woodman et al., 1993). When faced with experimental failures or personal problems during a long research process or journey to be a scientist as a long-term life goal, it is very important to regulate unstable and negative emotions in order
to continue with research. With this positive psychological capital, our participants were able to successfully develop and increase their emotional resilience in daily life and complete their degrees and research projects. Resilience often provides individuals with opportunities to overcome setbacks and take a leap beyond their original equilibrium (Bonanno, 2004; Luthans et al., 2006). In this process of emotional regulation, the formation of rapport with their advisor, the acceptance of positive and negative feedback, cooperation with fellow researchers, and interactions with other scientific groups functioned as crucial factors.

When the participants expressed scientific creativity to solve various problems, interactions with the advisor were significant, and the positive feedback of the advisor played a major role in the processes. The two participants also accepted negative feedback from the advisor. Increases in creativity are not only based on the leaders’ positive feedback but also on negative feedback. Podsakoff and Farh (1989) found that negative feedback improves performance more often than positive feedback, and Bono and Colbert (2005) also found that negative feedback positively affects behavior. A leader’s proper assessment and genuine feedback, excluding personal and emotional expression on the topics, can boost the group members’ scientific performance and positive behavior, leading to the development of their work capabilities (Ashford & Tsui, 1991) and the overall attainment of creative goals in the right direction.

Successfully developing the identity of a person often depends on how others (individuals, groups, and organizations) treat the person. Fair treatment is widely known as a major determinant of developing great self-assessment, especially pride (Lind & Tyler, 1988). Recognition and fair treatment of the participants by their advisor and colleagues was an important sociocultural condition for establishing their identity as scientists and stimulating their creative research. Receiving a research fellowship for their studies and having a chance to present their successful results at conferences helped them to successfully enhance their scientific creativity and grow as good postdoctoral researchers.

In summary, research of current scientists’ practices and experiences is meaningful from the standpoint of both scientific accomplishment and understanding scientific inquiry. In this study, we looked at the problems and obstacles that two postdoctoral researchers had to deal with and how they solved them using their scientific creativity while pursuing their degrees. We specifically described how they handled resource deficiency, faced scientific uncertainty, and established their personal identities as scientists. We also showed the importance of interactions between an advisor and graduate students and
among laboratory and other research colleagues. Our study provides information to future scientists who follow in the footsteps of other scientists in the problem-solving process in creative ways. Finally, the findings of this study may provide insight for science lab directors, such as advising professors, who must comprehend, support, and direct graduate students’ research.

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Ethical Considerations

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