REVEALING THE DECISION-MAKING PROCESSES OF CHEMICAL ENGINEERING STUDENTS IN PROCESS SAFETY CONTEXTS

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INTRODUCTION

Decision Making and Reasoning in the Context of Process Safety

Process safety incidents, ranging from the relatively minor to the catastrophic, are a major concern in the chemical engineering profession with impacts including lost time incidents, serious personal injury, fatalities, and negative public perception. These events can also have significant impacts on the environment and local infrastructure. However, many of these incidents could be avoided if better process safety management or risk mitigation was employed.[1, 2] For example, the fire and explosion that occurred at ExxonMobil in Baton Rouge was the result of operators manually opening a gearbox due to lack of familiarity with the equipment.[3] This incident could have been avoided if better maintenance or training procedures had been in place, if the operators had recognized the old valve had a different design than the new ones, or if the old valves had been switched to a newer valve design.[3] This accident indicates how process safety incidents can occur due to a series of decisions.

There are many ways process safety incidents are initiated, as commonly shown by the "Swiss cheese" model that represents potential failures in the different layers of protection as the "holes" in the cheese. When decisions result in the alignment of failures, an unsafe incident can occur. These potential failures can include human errors, poor management decisions, or knowledge deficiencies.[1] Process safety incidents are typically the result of failures at multiple protection levels; however, accident reports often try to ascribe fault to one cause of an incident, and that fault is usually attributed to a decision made by one person or a small group of people. After this singular "cause" is identified, the company can take action to correct the issue. The

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ExxonMobil incident demonstrates this simplistic approach is not always valid. It is important to analyze the mistakes made at every level of protection when investigating process safety incidents and near misses.

Process safety incidents are a result of a series of decisions that determine the success or failure of a protection level. Analyzing how decisions are made that lead to process safety incidents and near misses is essential to reduce process safety risks. Therefore, it is important to understand how individuals reason through decisions in the context of process safety. There is an important distinction between normative, or prescriptive, models that describe how decisions *should* be made and naturalistic, or descriptive, models, which more closely reflect how decisions are *actually* made in practice.[4] For example, recent scholarship in the context of process safety by Baybutt has verified that decisions made by process hazard analysis teams are not fully rational, but instead incorporate heuristics and cognitive biases.[5] Heuristics are not only required in ill-structured contexts, they are potentially beneficial because they allow for fast decision making with minimal cognitive effort and often provide decisions of reasonable quality. However, these mental shortcuts rely on cognitive biases rather than rationality and factual evidence, and so they can lead to distorted perspectives and decisions.[5, 6] In addition, emotions and other forms of automatic processing serve as a major player in all of the decisions that humans make. [7-10]

In this study, we focus on developing a better understanding of how senior chemical engineering students articulate their reasoning when faced with decisions in the context of process safety. By studying students' reasoning, we can understand the extent to which they do utilize thoughtful and effortful processing as opposed to relying on heuristics. Gaining a more nuanced understanding of how students approach process safety decisions at the end of their undergraduate training will inform future instruction so as to more effectively prepare engineers for the decisions they will face as practitioners.

Informal Reasoning

Research has been conducted to understand the types of reasoning that undergraduates use when making decisions that are complex and therefore require informal reasoning. Sadler and Zeidler identified three discrete types of informal reasoning used by students when making socio-technical decisions: rationalistic, emotive, and intuitive.[11] We believe this framework is useful in our study because of the similarities between socio-technical decisions and process safety decisions—they are both situated in the real world, are ill-structured, and do not possess a single correct answer. Rationalistic reasoning occurs when people use reason-based considerations, and is often rooted in logic or justifications that appear impersonal. Logical approaches are applied to the justifications of decisions, and include statements that are assumed as facts.[3]

Emotive reasoning occurs when decisions are made based on moral emotions, such as empathy or sympathy, and consideration of the well-being of how someone or something other than the decision maker may be affected. Emotive reasoning remains cognitive and logical, but considers perspectives or contexts beyond that of the decision maker.[11] Intuitive reasoning occurs when a decision is made based on an immediate feeling or "gut reaction" that results in an overall positive or negative reaction toward the problem. [11]

Sadler and Ziedler's study also found that there is potential for integration of multiple types of informal reasoning. The students in their study demonstrated the overlapping use of two or three different types of reasoning for a single decision. Additionally, students would often show intuitive reasoning in response to a decision, before contradicting themselves with emotive or rationalistic types of reasoning.[11] While we recognize that students must rely on multiple types of reasoning, we would expect to see rationalistic reasoning being utilized in support of their decision, in order to avoid an over-reliance on heuristics or biases, especially since students can be considered novices for decision making in the context of process safety.

Process Safety in the Classroom

The T2 laboratory incident in 2007 resulted in the injury of 32 employees and 28 civilians, and it ultimately led to the addition of "consideration of hazards" to the ABET, Inc. requirements for "Chemical, Biochemical, Biomolecular, and similarly named Engineering Programs" in 2012; as a result, many accredited institutions have found various ways to implement process safety into their classes or curriculum.[12] A literature review by Mkpat and colleagues documented 29 articles about the implementation of process safety into undergraduate classrooms between the years of 1999 and 2016.[13] The authors found that at the undergraduate level, curricula about process safety typically includes asset integrity and reliability, risk and hazard analysis, modeling of fires and explosions, and process safety management. Since there is no generally accepted curriculum for process safety in accredited institutions, universities are allowed to implement process safety into the classroom through a variety of methods as long as they meet the requirements for accreditation. For example, the South Dakota School of Mines created a section on reactive hazards as a collaborative effort between the faculty and engineers from industry. The module was implemented into a senior design course, and teaches safety about runaway reactions through the use of examples from the Chemical Safety Board (CSB), industry-focused lectures, and in-class and homework problems.[14] Leveneur and colleagues introduced process safety into a chemical reaction engineering course through the use of a numerical simulator. Following the modules on energy and mass balances and different thermal modes, students were shown a tutorial on how to model a batch reactor with multiple exothermic reactions, allowing them to learn how thermal safety assessment is done with these types of systems.[15] Students then had three weeks to complete a similar project on their own about a cooling system on an isothermal batch reactor.[15] The University of Michigan has created a comprehensive process safety curriculum that spans the entire chemical engineering curriculum with modules for different core chemical engineering classes such as thermodynamics, separations, and process control.[16] Many of these approaches focus on providing students with prescriptive models for decision making, but they do not assess the effectiveness of these methods on the students, much less study the naturalistic ways in which students actually make decisions in process safety contexts.

Engineering students are often taught to reason rationally through decisions when learning about process safety in the classroom, but emotive and intuitive influences are also prevalent in human decision-making in process safety situations. Emotive or intuitive influences may be difficult to capture or address in standard classroom assignments, but these factors impact decisions made in real-world scenarios. In order to better prepare students for the decisions they will have to make in their careers, their use of different types of reasoning in process safety decisions should be analyzed.

RESEARCH DESIGN AND METHODS

Research Questions

Our inquiry to understand the general process and types of informal reasoning that undergraduate chemical engineering students use when approaching hypothetical process safety decisions was guided by the following research questions:

1. How do senior chemical engineering students make process safety decisions?
2. What types of informal reasoning do students use when justifying their decisions?

In order to answer these research questions, we designed the study as described in the next section.

Methods

As part of this study, senior chemical engineering students were recruited to participate in a think aloud protocol where they talked through a series of hypothetical process safety scenarios. At the institution where the study took place, students are exposed to ethics and process safety instruction at various stages of the curriculum. All students learn about ethics in their first year multidisciplinary design course through introduction of case studies and discussions of the ethical decisions that were made that led to the reported outcomes. Later on, chemical engineering students have process safety instruction integrated as part of their senior plant design course. The hypothetical process safety scenarios came from the recently developed Engineering Process Safety Research Instrument (EPSRI).[17] The EPSRI consists of seven process safety dilemmas that could occur within industry and were constructed on the basis of reported incidents through the Chemical Safety Board as well as personal experiences of the faculty team performing the development. Each process safety dilemma requires respondents to make a decision based on three possible responses, followed by a series of 12-15 considerations for the individual to reflect upon and determine how much or little each consideration related to their decision.[17] An example of a process safety scenario from the EPSRI can be found in the Appendix.

Five senior chemical engineering students elected to participate in this study and they represented average students in the program. Smaller sample sizes are adequate when conducting qualitative research because the data collected tends to be rich in detail, isn't necessarily focused on prevalence, and can require an intense amount of resources to conduct proper analysis.[18] The purpose of qualitative research is not to generalize and predict, but rather to explore and explain. As such, the small sample size studied here is considered reasonable for the scope of the project. The think aloud protocol consisted of the student reading the process safety scenario, the decision prompts, and the considerations provided out loud while verbalizing their thought process. The students then explained their decision, and their ratings for the considerations on a scale from 1 (meaning "no" contribution to their decision) to 5 (indicating "great" contribution to their decision). Students were also provided with three additional questions focused on the different forms of informal reasoning (intuitive, emotive, and rationalistic). Field notes were taken during the think aloud protocol by the research team members that were present. In the initial sessions of the think aloud, the faculty member of the research team was present throughout the protocol, however it was observed that the students were looking to the faculty member for verification of their choices. For this reason, three of the five think aloud protocols were run with the faculty member of the research team only present for the first scenario after which the graduate student member of the research team stayed in the room for the remainder of the session to avoid any potential influence from a power dynamic on the data being collected. Student audio was recorded during the think aloud and the results were later transcribed for analysis. Proper human subjects' approval was obtained prior to conducting this study.

Transcripts from the think aloud protocols were later broken down based on dilemma to allow for observation of any similarities and/or differences in students' approaches to specific process safety situations. Although transcripts from all five senior chemical engineering students were included in the initial analysis, one student's data was later omitted as there was insufficient explanation of the responses to the process safety prompts to allow for a meaningful analysis of the data collected. This resulted in a total of 28 unique transcripts for analysis corresponding to four students' responses to the seven process safety scenarios.

Data Analysis

To address our first research question (*How do senior chemical engineering students make process safety decisions?*) we applied holistic coding. Holistic coding is a form of qualitative data analysis that seeks to examine the overall sense of the response rather than focusing in on line-by-line responses that may be provided.[19, 20] We selected this analytical coding approach for the first research question as it allowed us to capture a better understanding of the students' overall perspective and approach to making process safety decisions.

All of the transcripts were read by the first two authors of this paper. As the reading was performed, each researcher took notes on key themes that were emerging from the student responses and generated a holistic code book. Upon completion of this first read-through, the two authors met together to discuss the codes they identified to come to an agreement on the set of key ideas that were present within the data. The two research team members then went back through all of the transcripts using the finalized holistic code book to determine the holistic code that best applied to each transcript.

In addition to holistic coding, we addressed our second research question (*What types of informal reasoning do students' use when justifying their decisions?*) through the use of protocol coding. Protocol coding is prescriptive, which is appropriate when using an extant framework as a pre-established coding system.[19, 20] Here, we used the framework from Sadler and Zeidler including their three empirical types of informal reasoning to serve as our protocol for coding: rationalistic, emotive, and intuitive.[11]

Through several iterations of coding, we adapted this initial framework to fit our research needs due to the following difficulties. The original developers of the framework used "emotive" to describe something that was cognitive but "emotionally charged" p. 121.[11] Based on our transcript data, we found that it was difficult to identify when statements or reasoning were driven by emotion. Furthermore, it can be argued that emotions are inherent to all of our cognition,[7] so the operationalization of the code "emotive" was adjusted to instead be focused on the use of empathy, which was also included in the original definition. It was also noted that prompts that focused specifically on informal reasoning were generating responses that may have inaccurately reflected the reasoning applied by the students to the scenario (as can be observed by reading the interview protocol provided in the Appendix). In some cases, it appeared that these questions specifically prompted students to think with these types of informal reasoning, beyond what they had considered before being prompted for these types of reasoning explicitly. For this reason, these additional prompts were excluded from all additional data analysis.

Research Quality

To promote the quality of this interpretive research, we followed recommendations during both the making and the handling of the data, as advised by other qualitative researchers in engineering education.[21, 22] This scholarly work provides six categories for validation or reliability that should be designed into the study in order to promote quality: theoretical validation, procedural validation, communicative validation, pragmatic validation, ethical validation, and process reliability. Details for how we addressed these ways of building quality into an interpretive research study are provided in the following two sections.

Making the Data

The think aloud protocol was designed to leverage prior work in the literature by Sadler and Zeidler to ensure theoretical validation.[11] As described previously, students were provided with prompts that would encourage them to reflect on the types of informal reasoning they had applied in the context of their response to the scenario. The modification of the think aloud protocol based on the observed power dynamic was an example of adhering to procedural validation. Changing the research team personnel assisting with data collection from including the faculty member and graduate student throughout the entire process to just the graduate student after completion of the first scenario helped collect data that was more accurately representative of the targeted student population and avoided the introduction of any potential bias. Communicative validation was ensured by having the students provide their impressions directly without any additional prompting from the research team. Students were only provided with additional clarifying information when it was requested and this information was kept to a minimum to ensure the data accurately represented students' decisions and justifications. As students moved through the EPSRI, they were provided the opportunity to change their decision or modify their answers if the considerations prompted them to look at something differently. This method helped ensure that the knowledge was being accurately constructed within the relevant community. The use of the EPSRI, a survey designed with scenarios for the educational level of senior chemical engineering students, with a population of senior chemical engineering students served as a means to attain pragmatic validation. Finally, process reliability was ensured through the collection of data using audio recordings and the transcription of these recordings through a third party data source. An audit trail was also maintained to track any changes that were made to the data collection methods.

Handling the Data

Using the qualitative research framework outlined in Walther et al., we were able to take several steps to ensure research quality when handling our data.[21, 22] In order to address procedural validation, we maintained an audit trail of our iterative coding process. In addition, two members of the research team assigned holistic codes for each transcript and thoroughly discussed any misalignments in interpretation before finalizing. We also engaged in training for the use of our protocol, coding across three of the seven process safety dilemmas: iterating, discussing misalignments, and adjusting our process in order to reach an ability to consistently code. To perform this process we collaboratively coded using Dedoose, a web-based platform that allows for collaborative qualitative data analysis. From there, we individually coded the remaining four dilemmas, then confirmed each other's use of the coding system. Pragmatic validation was addressed, at least in part, by continuous reading of related decision-making literature in order to map our coding process onto other accounts of the social reality around understanding decision-making from a descriptive paradigm. This included several popular texts as well as academic texts.

RESULTS AND DISCUSSIONS

Research Question #1

The first research question sought to understand how senior chemical engineering students make process safety decisions. Using holistic coding, we were able to identify four overarching themes that were present within the data set. The first theme we labeled "**Better Safe than Sorry**," and this theme appeared in 18 out of the 28 responses analyzed (64.3%). "Better Safe than Sorry" can be characterized as when students would review the process safety scenario provided, identify a potential safety related issue, then apply this observation as the basis for their decision and refuse to examine other factors that may have an influence on the final decision. An example of this approach to a scenario from Student 2 is shown below:

> *"Just because it's better to be more safe than not safe enough."*

Another example of this approach to a scenario was observed in a response by Student 4:

> *"...I think ignoring this probably won't lead to an issue at the moment, but better safe than sorry, honestly, with people's lives and money on the line."*

This theme seems to demonstrate students' tendency to give the easiest answer, which is to always err on the side of safety. Because these scenarios are hypothetical, students are only presented with the basic information about the process safety decision, and they lack the contextual awareness that would exist in reality to complicate the situation and decision-making process. In addition, we recognize that "Better Safe than Sorry" is the simplest response and therefore potentially the most appealing due to its minimal cognitive load when compared to more nuanced considerations of such a decision.

"**Acknowledging Complexity**" was another prevalent theme observed in student responses. This theme was found in a total of 8 of the 28 responses (28.6%). In these responses, students would articulate how there were multiple perspectives that were important to consider when making a decision. This approach may not have changed the final decision that they made, but it did demonstrate a realization that there were other factors that could be involved in the decision-making process. Student 1 showed this approach clearly in their response to a scenario about whether you would request operators to stay at a plant with an approaching hurricane in the following quote (acknowledging complexity element showed in bold):

> *"Now I'm weighing it on, if you do send volunteers and it all works out,* ***you saved surrounding neighborhoods and the environment from all these bad things that could happen at the expense of, worst case scenario, a couple people who volunteered to be there, even.*** *Now looking at it as if you're trying to save people at your company, but it could be at the expense of a lot more than just a couple people at your company, who would volunteer."*

Two additional themes were identified within student responses although they were not very prevalent within the data set. **"Indifference"** was observed in a single student's response to one of the scenarios. In this case, the student did not seem to demonstrate a strong commitment to their decision overall and were really okay with either option that was provided to them. Another theme that only appeared once in the data set was **"Proposing Alternative Solution."** In this theme, the student would describe how the available options weren't adequate and that a different alternative should be followed although they may not have been able to articulate what that solution should be.

These results seem to indicate that students are making "rule-based" decisions based on what they have been taught is appropriate for engineers in a process safety context. In other words, they appear to be in a predictive phase of behavior, where they are identifying these situations as "ethical" and as such are approaching making their decisions to be as safe as possible.[23]

Unfortunately, it has been observed that in our daily decisions, humans do not necessarily recognize situations as being "ethical" that can impact the decisions we are making.[24] For this reason, it is important that we provide an opportunity for senior chemical engineering students to participate in process safety decisions as part of their regular design based activities, allowing them to recognize the additional complexities that go into final decisions and that the decisions may not be as straightforward as initially assumed.

Research Question #2

In terms of the second research question (*What types of informal reasoning do students use when justifying their decisions?*), we see that students use rationalistic and emotive types of informal reasoning most often, and they use intuitive reasoning the least, as quantified in Table 1.

TABLE 1
Quantification of protocol code occurrence

Type of Reasoning	**Rationalistic**	**Emotive**	**Intuitive**
Frequency	211	94	16

As students reason through decisions, they consistently verbalize rationalistic reasoning—this type of reasoning is dominant in terms of frequency. This pattern is not surprising as slow, rational reasoning is the most expected form of reasoning in Western society, especially in engineering contexts. In addition, it is the easiest to articulate. For example, a quote from Student 4 demonstrates the use of rationalistic reasoning:

> *"Because if you are breaking the law by not inspecting it as much as the law requires, then that's a big issue right off the bat. That shows negligence. It shows not caring and a bad culture."*

In similarly cognitive chains of reasoning, participants also integrated the consideration of others (e.g., workers, the environment) demonstrating the use of emotive reasoning when weighing different considerations related to the safety decision, as represented by a sample quote from Student 2:

> *"'Cause I feel like immediate impact to human lives is slightly more important than the immediate impact to the environment. 'Cause the environment can eventually be cleaned up whereas if someone were to die from this, it'd be very bad."*

Although it was least common, we did find evidence that students used intuitive reasoning, which occurred in the format of the following quote from Student 1:

> *"As soon as it said that it can contaminate the water of nine counties surrounding the river, that kind of made me make my decision almost immediately"*

Participants typically made their initial decision and verbalized limited reasoning—as they progressed through the EPSRI we were able to see deeper into the ways in which they used different types of reasoning. These types of reasoning were almost always in alignment with their initial decision—the reasoning comes across more as justification. In other words, the majority of our data was collected after the students had made a decision (per the protocol), not before. This outcome maps well onto established literature framing decision making as 'naturalistic' when it is studied descriptively.[25, 26] In descriptive studies of decision making, individuals rarely actually generate multiple options and then reason through them in the ways that rational models prescribe. Instead, people tend to generate an idea or decision, and then spend time cognitively 'checking' the feasibility of the decision, or justifying it.[24] Similarly, despite being given multiple possible ways of handling the decision, our participants spent less time reasoning between options that align with the best predicted future, and more time building a coherent justification for how the decision they had already committed to made sense. This finding also connects to previous findings—in the originally cited study by Sadler and Zeidler, where the three types of informal reasoning emerged, the researchers found that when participants had a strong intuitive reaction, their following reasoning didn't change the decision, but rather built evidence in support of that intuitive reaction.[11] Significant research aligns with this model for human decision making—we go with our initial intuition, and then we craft our reasoning as justification, having already made the decision.[11] Additionally, this model is supported by studies on cognitive dissonance theory, in which inconsistencies in a subject's thoughts lead to a state of psychological discomfort. The subject then tries to alleviate this discomfort via a variety of coping methods, such as justification or rationalization. In our example, students making a strong intuitive decision may have been attempting to rationalize or justify sticking with this decision because this action would decrease their psychological stress, especially if presented with conflicting or contradictory information.[27, 28] This behavior is in significant contrast to the common prescriptive models of decision making often portrayed in engineering, which assume rational consideration of utility, and disregard the role of intuition.

CONCLUSIONS

Chemical engineering students that are set to graduate need to be prepared for how to approach process safety decisions. Unfortunately, the majority of our instruction in this area focuses on identification of hazards and models for risk management with little time devoted to the complexities associated with the decision-making process itself. This study analyzed the decision-making process and use of different types of informal reasoning of five senior chemical engineering students as they made process safety decisions. Results included that students most often decide to be "better safe than sorry," and they did not acknowledge the complexities associated with the decisions in many cases. Students would then justify their decisions by rationalizing and showed limited empathy towards others that could be impacted through the decision-making process. It is important to note that this work was limited to just five individuals that volunteered to participate in this study although only four datasets were analyzed due to reasons outlined in the Methods, and as such may not yet be transferrable to other contexts without further investigation. This work serves as a reminder that as chemical engineering educators we must contextualize process safety decision-making as part of the design process and not only focus on the procedure, but draw students' attention to the thought process as well. By ensuring that our students think more broadly about the implications of the decisions they make in the process safety space and the possible reliance on heuristics or biases during their decision making process, it may be possible to provide them with a better understanding for how decisions of these kind will take place in industry.

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APPENDIX

Example ESPRI Scenario

You are an engineer working at a chemical company. One of your responsibilities is to file accident reports in the event of chemical spills on land owned by the company. An accidental chemical spill occurs when a product is being loaded into a truck by a contracted shipping company. Routine medical screenings of those exposed to the chemical during the spill indicated no one was harmed, but the spill is large enough that you have to file a report with the state's department of environmental management. In a meeting with your plant manager, you are informed that there have been multiple spills before, and any spill large enough will carry a hefty fine from the state when it is reported. Since the amount of chemicals spilled was only a few gallons over the limit that needs to be reported to the state, your plant manager tells you to alter your report to avoid paying the fine. "It's barely over the limit! We can't afford a fine right now. We'll have to lay people off," says your manager. You protest, but your manager interjects, "Look, it's in both the best interests of the company and yourself to avoid that fine. Do what you have to do." When you return to your desk, your co-worker Pam informs you that the plant manager had put similar pressure on the last person who occupied your position. Pam isn't sure if that individual was fired or if they resigned, but they vacated that position soon after the plant's last chemical spill.

What should you do?

o Listen to the plant manager and change the report

o Can't decide on a course of action

o Submit an accurate report of the chemical spill

<u>Rate the following issues in terms of importance (1-5) where 1 represents "Great" and 5 represents "No".</u>

Note that some of the items may seem irrelevant or do not make sense. In that case, rate the item as "No" importance and do not rank the question.

1. Are you concerned about your management of the spill affecting your job security?
2. Is it possible that your co-workers might lose their jobs when you file the report?
3. Who would be the most impacted by the spills?
4. How long has Pam worked for the company?
5. Are you concerned your boss will make life difficult for you if you report the spill?
6. What would be the negative impact on your family or dependents if you lose your job?
7. What if the next chemical spill has an impact on you personally?
8. What are the long term environmental impacts if the spills continue unreported?
9. Is it ever okay to purposefully misrepresent data?
10. Is it in the company's best interest for you to avoid reporting the spill?
11. What is your desire to continue to work for an employer who doesn't follow protocol correctly?
12. Can you avoid being placed in the same position as the previous engineer who was put under pressure while preparing the report?

Interview Protocol

The data that will be collected as part of this study will be audio recordings of the students as they talk through the EPSRI. This process will include their expression of what decision they would make as well as which of the prompts included on the protocol they considered. Participants will also be asked follow-up questions to further capture their thought process. The researcher conducting the think aloud study will also take field notes on any relevant behaviors from the participants such as tapping their pen/pencil, closing their eyes, etc. After completion of the EPSRI the students will be asked the following question:

There are different ways to reason through decisions. I'm going to ask you to talk about the decision you just made when responding to the EPSRI with respect to three distinct aspects of human reasoning: rational, intuitive, emotive.

i. First, **rational**. This type of reasoning utilizes reason and logic and is often impersonal. What role did rational reasoning play?

ii. Second, **intuitive**. This type of reasoning utilizes immediate reactions, or gut-feelings. What role did intuitive reasoning play?

iii. Finally, **emotive**. This type of reasoning utilizes empathy or an understanding of the experiences of other people. What role did emotive reasoning play?