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RESEARCH ARTICLE

The Role of Prior Knowledge and Abductive Reasoning in Pre-service Elementary Teachers' Scientific Experimental Design Process

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ABSTRACT

The purpose of this study is to explore how prior knowledge influences thinking strategies and patterns of abductive reasoning during the experimental design process in life science contexts. The participants were 23 pre-service elementary teachers (6 male, 17 female) from a teacher education university. To examine the influence of prior knowledge, two tasks were employed: a familiar task based on the curriculum where participants possessed prior knowledge, and an unfamiliar task lacking direct experience. Participants completed the tasks sequentially, and their design artifacts and post-interview data were comprehensively analyzed. The results are as follows. First, while the experimental design process followed a five-stage reasoning flow, fundamental approach strategies differed based on task familiarity and predictability. In the high prior knowledge task, participants primarily utilized a 'hypothesis-deductive approach,' systematically controlling variables based on existing knowledge to perform 'scientific design.' Conversely, in the unfamiliar task where outcome prediction was difficult, an 'exploratory approach' emerged. Participants relied on intuition and experience to construct verification logic, shifting towards 'engineering design' with the practical goal of realizing observable phenomena. Second, this paradigm shift was accompanied by a change in the functional role of abductive reasoning. Under 'scientific design,' 'selective abduction' mainly performed a complementary function to stabilize the design by supplementing existing frameworks. However, in the transition to 'engineering design,' 'creative abduction' was actively utilized for its generative function to overcome uncertainty and devise new experimental conditions. This study is significant as it reveals that learners flexibly switch design paradigms in response to uncertainty and strategically adapt their use of abductive reasoning, thereby providing a new framework for understanding adaptive thinking strategies.

Keywords: Science experimental design, pre-service elementary teachers, abductive reasoning, prior knowledge, cognitive processes

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Introduction

Scientific inquiry learning involves learners autonomously formulating questions, establishing hypotheses, designing and conducting experiments, and evaluating evidence. This requires analyzing problems based on background knowledge and actively constructing appropriate methods (Abdi, 2014; Moeed, 2013). Experimental design is a complex cognitive activity demanding higher-order thinking (Karelina & Etkina, 2007). It transcends the technical manipulation of variables, involving deep cognitive processes such as planning comparative structures and organizing conditions (Sirum & Humburg, 2011; Xiantong et al., 2019). Effective design requires distinguishing independent, control, and dependent variables, while considering repeated trials and measurement strategies for reliability (Kuhn, 2016; Veermans et al., 2006). Success depends on competencies like recognizing inquiry goals (Millar et al., 1994), applying control-of-variables strategies (Hammann et al., 2008; Klahr et al., 2019), and understanding reflective elements of measurement (Arnold et al., 2014).

However, inexperienced learners often struggle with systematic variable control or perform manipulations misaligned with experimental goals (Klahr et al., 2019; Zhou et al., 2016). These challenges highlight the importance of prior knowledge—defined as the learner's background knowledge combined with direct and indirect experiences. Prior knowledge helps learners understand variable relationships and determines the effectiveness of instructional support (Kalyuga, 2007; van Riesen et al., 2022). It also shapes problem-solving approaches: learners with high prior knowledge use systematic strategies and interpret results accurately (Bumbacher et al., 2018; Stender et al., 2018), whereas those with limited knowledge rely more on trial and error (Lazonder et al., 2010).

Abduction is a key reasoning mode that advances thinking when prior knowledge is incomplete (Klichowicz et al., 2021; Paavola, 2004). It involves introducing new ideas or deriving defeasible conclusions from limited information (Aduriz-Bravo & Sans Pinillos, 2023; Peirce, 1958). Abduction is classified into selective and creative abduction based on novelty (Magnani, 2005; Schurz, 2008). Selective abduction involves choosing an explanation from existing hypotheses, while creative abduction generates new ideas to expand knowledge (Magnani, 2005). Scientists often construct solutions incrementally by referencing similar cases rather than inventing entirely new models (Clement, 2022; Nersessian, 2025), a process mirroring abductive reasoning. In science education, abduction is studied as a core strategy for explaining surprising phenomena and generating hypotheses, influenced by the learner's prior knowledge (Lazonder et al., 2009).

Difficulties in experimental design due to limited prior knowledge are closely linked to inquiry goals. Previous studies distinguish between "scientific design," aiming to understand causal relationships, and "engineering design," aiming to produce desired outcomes (Schauble et al., 1991). Scientific design focuses on identifying causes through systematic variable control, while engineering design seeks practical solutions under given conditions. In uncertain situations where prediction is difficult, learners may prioritize engineering goals (implementing phenomena) over scientific goals (hypothesis testing) (Zimmerman, 2005).

However, exploration remains insufficient regarding how the overall experimental design process unfolds based on prior knowledge levels or task familiarity, and how abductive reasoning—an effective mode of thinking for creative problem-solving—functions within this process. Existing literature has largely remained at the level of describing the impact of prior knowledge on experimental strategies (e.g., Kwon et al., 2006; Lazonder et al., 2009). Studies that sufficiently explain the specific cognitive processes through which learners utilize available knowledge to construct the entire design process are scarce. In particular, pre-service elementary teachers, as "generalists"—unlike secondary teachers who are specialists in specific science domains—possess relatively insufficient scientific background knowledge (Garcia-Carmona et al., 2017). Consequently, they are highly likely to encounter uncertain inquiry situations. Therefore, elucidating the reasoning strategies they employ to bridge knowledge gaps is an essential prerequisite for enhancing their future inquiry instruction competencies (Moeed, 2013).

Accordingly, this study analyzes the reasoning processes of pre-service elementary teachers across two inquiry tasks with different prior knowledge contexts. The goal is to elucidate the influence of prior knowledge on inquiry goal setting and abductive reasoning patterns, and to identify the relationship between resource utilization and design patterns. The specific research questions of this study are as follows:

1. What are the experimental design thinking processes and strategies of pre-service elementary teachers in two tasks with differing prior knowledge contexts?
2. How do prior knowledge and abductive reasoning interact in the experimental design process of pre-service elementary teachers?

Methods

Participants

The participants were 23 students (6 males, 17 females) majoring in elementary education at a university of education, ranging from first to fourth year. Specific background information, including grade level, advanced major, and completion of science-related courses, is presented in Table 1. All participants completed two experimental design tasks followed by individual interviews. Participation was voluntary; written informed consent was obtained after providing a full explanation of the study's purpose and procedures. This study was approved by the Institutional Review Board (IRB) of the affiliated university.

Table 1. General background and science coursework of participants

Participant ID	Year	Major Concentration (education)	Number of Science Courses Taken	Participant ID	Year	Major Concentration (education)	Number of Science Courses Taken
P1	1	Science	2	P 13	2	Physical	1
P2	1	Science	2	P 14	2	Art	1
P3	1	Science	2	P 15	1	Science	2
P4	1	Science	2	P 16	3	Art	2
P5	2	Physical	1	P 17	1	Korean Language	0
P6	2	Physical	1	P 18	2	Social Studies	1
P7	2	E lementary	1	P 19	4	Music	2
P8	2	Physical	1	P 20	3	Elementary	2
P9	2	Physical	1	P 21	2	Korean Language	1
P 10	1	Mathematics	0	P 22	2	Mathematics	1
P 11	1	Music	0	P 23	2	Physical	1
P 12	2	Elementary	1				

Data Collection

To investigate how pre-service elementary teachers utilize prior knowledge during experimental design, two inquiry tasks with contrasting levels of prior knowledge availability were employed. Task 1 involved designing an experiment to test the hypothesis that "seeds require an appropriate amount of water to germinate." Since similar experiments are covered in the elementary school curriculum, this represents a "structured task" where participants can formulate a scientifically accurate design based on abundant prior knowledge. In contrast, Task 2 required designing an experiment to test the hypothesis that "honeybees can distinguish colors." This topic is not addressed in the regular curriculum, so participants were expected to lack direct experience or knowledge. This task entails higher difficulty and uncertainty than Task 1, as the "correct" answer is not immediately apparent, and it involves animal behavior, which is challenging to control. By leveraging these differences, the study aimed to contrastively observe how learners bridge knowledge gaps and develop reasoning when prior knowledge is absent or uncertain. Both tasks belong to the biological domain, enhancing comparability.

Participants performed the tasks sequentially, completing Task 1 before proceeding to Task 2. Given that the content domains were independent (plants vs. animals), it was determined that the execution of Task 1 would unlikely induce direct learning transfer to the content knowledge required for Task 2. Participants were instructed to record the materials, procedure, a simple diagram of the process, and their confidence level (the extent to which they believed their design was logically valid for testing the hypothesis). Subsequently, individual interviews were conducted to collect data on the cognitive processes engaged during the tasks. The interviews focused on initial ideas, prior knowledge serving as key judgment criteria, and decision-making standards in uncertain situations to identify in-depth thinking processes and patterns of prior knowledge application. All interviews were audio-recorded for analysis. When further clarification was required during analysis, supplementary information was collected via telephone or text message.

Data Analysis

To analyze the thinking processes manifested in the pre-service elementary teachers' experimental design, data sources included interview recordings, experimental design worksheets, and researcher observation logs. Qualitative analysis methods were employed to identify the flow of thought and patterns of prior knowledge utilization within the experimental design process. First, all individual interview recordings were transcribed. Initial coding was then performed by repeatedly reviewing the transcripts using the Open Coding procedure proposed by Strauss and Corbin (2015). This process involved unitizing thought flows—such as major cognitive activities, application of prior knowledge, responses to uncertainty, and reflections on validity—and assigning representative codes. For example, the statement "I recalled the Pavlov's dog experiment I learned before" was assigned the code "Borrowing Knowledge from Other Fields." Subsequently, the segmented codes were inductively categorized based on similar or repetitive thinking processes, and the characteristics of thinking patterns by task type (Task 1 and Task 2) were summarized. The categorized thought flows were reconstructed in chronological order, and the developmental patterns of the experimental design process for each task were visually schematized. This schematization aimed to clearly reveal the stepwise flow of thought participants experienced during experimental design. Based on this, the patterns of experimental design were compared between task types, and the methods and contexts of prior knowledge utilization were analyzed. This procedure focused on precisely capturing the participants' thought flow and deriving the underlying cognitive processes involved in experimental design.

To enhance the objectivity of data interpretation, a triangulation strategy (Patton, 1999) was utilized to cross-reference various data sources, including design worksheets, interview data, and follow-up questions. Throughout the analysis, priority was given to interpretations based on participant discourse, aiming to minimize researcher bias or hypothesis-driven interpretation. Finally, the analyzed results were reviewed by one science education expert and two fellow researchers to ensure the reliability of the analysis.

Results

Typical cognitive strategies and developmental patterns were derived by initially coding major cognitive units and categorizing recurring thought flows observed in the pre-service teachers' experimental design processes. Based on these findings, the experimental design process was structured into five stages: (1) Problem Recognition, (2) Construction of the Experimental Problem Space, (3) Strategic Use of Prior Knowledge for Hypothesis Testing Logic, (4) Specification of Experimental Conditions and Development of the Experimental Design, and (5) Review and Refinement of the Design. While this classification draws upon the SDDS model by Klahr and Dunbar (1988) and the experimental design diagram by Baker and Dunbar (1996), it was modified and supplemented to reflect the specific cognitive processes identified in this study. Although these stages are presented in chronological order, overlapping patterns were observed in participants' actual discourse; for instance, the setting of independent variables and the activation of relevant prior knowledge frequently occurred simultaneously.

Experimental Design Process and Strategies in Task 1

Task 1 presented a hypothesis allowing for the clear identification of independent and dependent variables. Throughout the design process, pre-service teachers primarily developed their reasoning by recalling experimental experiences and scientific knowledge directly related to the hypothesis. They navigated the experimental design through the following cognitive flows, which occurred recursively as needed rather than following a strictly linear progression.

Problem Recognition

Upon encountering the task, participants focused on the presented hypothesis statement. Depending on the depth of their interpretation, the flow of thought diverged into two paths. Most participants immediately identified water as the key element and clearly established the experimental goal as "verifying the causal relationship between water and seed germination." Having intuitively grasped the hypothesis's meaning, they followed a "Variable Structure-Oriented Path (Path A in Fig. 1)," rapidly advancing to the Construction of the Experimental Problem Space to specify variables.

Conversely, some participants focused on the ambiguity of the phrase "appropriate amount of water," seeking first to resolve uncertainties regarding which seeds to use or specifically how much water to apply. Two participants explicitly inquired, "What specifically does 'appropriate amount' mean?" This represented an attempt to follow a "Meaning-Oriented Path (Path B in Fig. 1)," aiming to explore additional information or background knowledge to clarify the operational definition of the hypothesis. Thus, the problem recognition stage manifested as a process of confirming the hypothesis's meaning and establishing the experimental focus. Relevant statements from the pre-service teachers are as follows:

P04: "My first thought was, ***'What does this hypothesis statement actually want to discover?'*** *... I debated whether it meant varying the water levels in each beaker to see at which amount seeds germinate best, or simply determining if water is needed at all. Since [I was told] either interpretation was fine, I considered* ***which would be more convenient and decided the latter would allow for a faster experiment.****"*

P14: "First, looking at the hypothesis that an appropriate amount of water is needed... I thought about this condition? I mean, ***I first considered what condition was being investigated.*** *... But since it said 'appropriate amount,' I was a bit confused about whether I should focus solely on water and exclude other conditions like sunlight, or* ***specifically how much 'appropriate' actually meant.****"*

P21: "First of all, ***it seems this experiment involves a hypothesis related to water.*** *So, while there are many conditions for plant growth, I thought, 'I will proceed with the experiment considering* ***water as the most important condition among them.'"***

Construction of the Experimental Problem Space

After recognizing the problem situation, the pre-service teachers constructed an "Experimental Problem Space"(Klahr & Dunbar, 1988), a psychological search space for establishing relationships between variables and defining the scope of manipulation and control. Within this space, they clearly specified independent and dependent variables based on the given hypothesis and established the fundamental structure requiring the control of remaining conditions. Most participants, recognizing the importance of the "appropriate amount of water" identified in the problem recognition stage, classified the "amount of water" as the independent variable and "seed germination" as the dependent variable. Furthermore, they immediately applied the "Control of Variables Strategy (CVS)," dictating that all variables except the amount of water be kept constant. This demonstrates that the "systematic manipulation and control of variables"—logically excluding extraneous variables that could affect causality—served as a core strategy for experimental design. In essence, this stage involved establishing the basic frame of the experimental design, thereby setting the prerequisites for devising subsequent methods. Relevant statements from the pre-service teachers are as follows:

P7: "Obviously, since ***water is the variable and the object I want to observe****, everything else must be identical. That is the only way to know if water is truly necessary."*

P16: "Since I established the hypothesis that water is needed, ***I thought everything other than water should be kept the same;*** *thus, I considered variable control to be important."*

P4: "I thought seeds and water were the most necessary items because ***there are independent and dependent variables. Water acts as the differing factor****, while seeds are required as a basic condition, so I selected seeds and water [as materials]."*

The statements from P7 and P16 reveal a shared understanding: they identified "water" as the independent variable from the hypothesis and established that all other conditions must be controlled and kept constant. Notably, as their prior knowledge regarding the task was clear, they adopted a "hypothetico-deductive approach," applying existing knowledge to hypothesis verification without hesitation. Meanwhile, P4 illustrates the process of identifying key variables required for the experiment and conceiving the basic structure based on them.

Strategic Use of Prior Knowledge for Hypothesis Testing Logic

Immediately after structuring the experiment, pre-service teachers adopted and concretized the logic of a "Comparative Experiment" as a core strategy for hypothesis verification. They rapidly activated prior knowledge related to "standardized experimental models" stored in memory—such as elementary or middle school textbooks, classroom experiences, and video materials—to devise specific experimental methods. During this process, they established typical scientific inquiry strategies, determining how to divide experimental and control groups or how many condition groups to establish. Judgments such as "divide into a watered group and a non-watered group" or "set water amounts at various levels" were made at this stage.

The prior knowledge recalled by participants varied; experimental experiences or textbook conceptual knowledge from elementary and secondary curricula were most frequent, while some utilized university lectures, reference videos, or personal experiences. Relevant statements are as follows:

P6: "I am taking a science education course... someone presented on the unit about plant growth conditions and ***showed a reference video experimenting with kidney beans for 'the process of seed germination.' That came to mind****, so I designed the experiment this way."*

*P11: "**I had an experience growing kidney beans in elementary school**. I recall using soil back then, so I thought of soil first."*

*P18: "**Background knowledge that three conditions are needed for seeds to sprout came to mind first.** Those three are soil, appropriate sunlight, and water... So I decided to design the experiment using only two pots: one with water and one without."*

These statements reveal that P6 recalled video materials from a university class as a "successful experimental model" and attempted to replicate the tools and procedures in their design. P11 recalled an elementary school experiment involving plants and planned to use the materials from that experience. Similarly, P18 retrieved scientific knowledge regarding germination requirements and planned a comparative experiment based on it. Among the 23 participants, 13 recalled knowledge or video viewing experiences related to germination conditions, 6 recalled previous experiments using plants, and the remaining 4 recalled daily life experiences of planting and growing seeds. This indicates that prior knowledge was not merely listed but served as the rationale for determining the core experimental strategy of "how to compare."

Specification of Experimental Conditions and Development of the Experimental Design

Having established the basic frame of the experiment, pre-service teachers concretized it into an executable design. In this stage, they organized materials, detailed procedures, and measurement methods one by one, specifying the variables set in the initial phase and filling in the design framework. Here, the experiences and knowledge activated in the previous stage were not merely recalled but served as grounds for determining specific experimental conditions.

P14: "(In a video I saw in science class), ***they placed a paper towel at the bottom and wet it, and [the seeds] seemed to grow.*** *So, I did it similarly to the video."*

*P15: "**Since we used pots back then (in a high school plant experiment), I felt a connection that pots would be necessary**. Also, although it was different, we used beakers to adjust concentration for a pH experiment. Because of that association, beakers appeared in my design."*

P14 applied the tools observed in a past video directly to the choice of planting medium, while P15 specifically reflected the use of pots and beakers based on high school laboratory experiences. This reveals a pattern where prior experiences were directly transformed into experimental conditions.

Furthermore, participants detailed the duration, frequency, and method of watering to ensure variable control.

*P3: "**(Water for 5 to 7 days at the same time every day).** I did this before... the instructions said to grow it in a dark environment for 5 to 7 days while watering. It was written like that."*

*P21: "Common sense dictates that when we plant plants, we don't water them just once. **Watering an appropriate amount so it doesn't dry out, but not too much so it doesn't rot... doing that helps germination**."*

As shown, pre-service teachers moved beyond merely identifying variables to strictly controlling experimental conditions by specifying the period, frequency, and amount of watering. However, in post-interviews, some participants expressed uncertainty regarding the appropriateness of these control variables. For instance, doubts arose about what specifically constituted an "appropriate amount" of water or whether using pots instead of petri dishes was valid. When specific knowledge regarding experimental procedures was lacking or uncertain, participants recombined indirect knowledge or relied on intuition. Most inferred appropriate conditions using daily experiences or vaguely retained knowledge.

*P8: "It wasn't that it was ambiguous, but since **I didn't know the seed type**, I thought germination speeds would vary. **I recalled not doing the experiment for two weeks in elementary school,** so I deliberately set a longer period and wrote down two weeks."*

*P11: "The reason I decided (on the amount of water) was... **I felt if it exceeded 500ml, there would be more water than soil.** I thought 100ml would be enough to show a distinct difference, so I set it at 400, 300, 200, and 100ml."*

*P12: "For peas... I feel like I heard this somewhere, or maybe not, but vaguely **I recall hearing that peas grow quickly and are easy to raise.**"*

P8 decided on a two-week duration based on past experimental experience amidst uncertainty about the timeline. P11, struggling to determine the water volume per pot, intuitively specified "appropriate amounts." P12 selected peas based on uncertain but recalled knowledge.

Additionally, some pre-service teachers tentatively assumed experimental results while specifying conditions. These predictions were primarily based on past experiences or knowledge, recalling tentative conclusions regarding the hypothesis.

*P5: "**I think (the hypothesis) is true**. The basis is that I saw it with my own eyes in a video, so I thought it was obvious."*

*P8: "I **thought seeds would germinate where water was sprayed... and not where it wasn't.** Since I had done this experiment before, I remembered the result. It feels more like experience than inference."*

Review and Refinement of the Design

After outlining the materials and procedures, some pre-service teachers re-examined whether their designed experiment could validly test the hypothesis, reviewing the logical validity of the procedures. Unlike the intuitive prediction of results during the condition-setting phase in the previous stage, this process involved mental simulation—visually imagining images or videos of the established conditions—to review the design against actual execution scenarios and address deficiencies.

*P12: "**I thought, 'Let's try three pots,' but then wondered, 'Is it really necessary? Wouldn't two be enough?'** ... But if I used two—one with no water and one with water—I thought the plant might not grow well depending on whether the amount was too much or too little. **To see the results more certainly,** I settled on three: the maximum amount, none, and an intermediate amount."*

P12 considered the necessity of increasing the water quantity conditions from two (water vs. no water) to three (high, none, medium). This was intended to reduce uncertainty in results and enhance the validity of hypothesis testing, exemplifying an attempt to improve experimental completeness by reconsidering specific variable conditions.

*P20: "I thought that just writing down the results would allow children to see the differences or understand the experimental outcome, **so I debated whether the final step was strictly necessary**. ... But I felt there should be a time to summarize everything once more, so I decided it was needed and wrote it down."*

Furthermore, P20's case demonstrates that participants did not stop at reviewing validity at the condition level but also reflectively examined the structural completeness of the entire experimental process.

Through the analysis thus far, major cognitive stages ranging from Problem Recognition to Review and Refinement were derived based on pre-service teachers' discourse. These stages developed interactively based on prior knowledge and empirical judgment. Fig. 1 schematically illustrates the typical cognitive paths observed in the step-by-step process of Task 1.

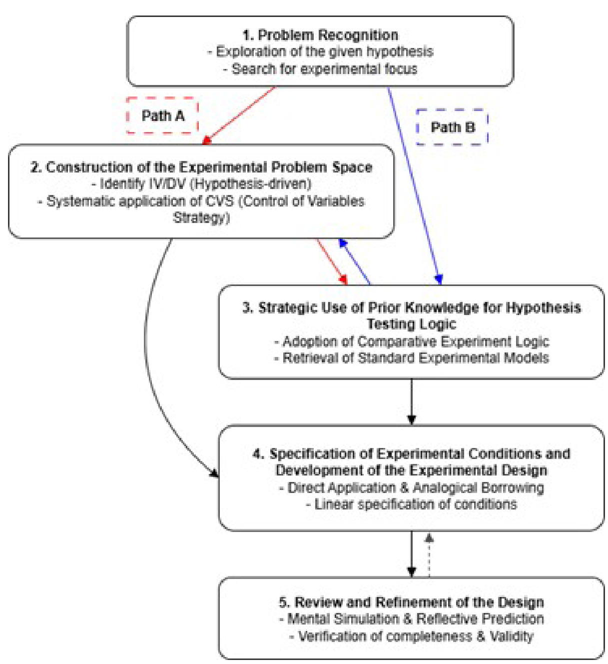

Fig. 1. The experimental design process of elementary school pre-service teachers as shown in task 1

Experimental Design Process and Strategies in Task 2

Upon encountering Task 2, pre-service teachers found it challenging to grasp the structure of variables. Consequently, their experimental design process centered on exploratory thinking for problem-solving rather than the retrieval of relevant prior knowledge. Notably, processes of constructing alternative explanations or generating new ideas amidst uncertainty were prominent. They designed the experiment through the following cognitive flows, which, as in Task 1, proceeded recursively as needed.

Problem Recognition

Since Task 2 involved an unfamiliar topic not covered in the regular curriculum, participants did not immediately grasp the hypothesis's meaning. Instead, they read it repeatedly, exploring where to focus the experiment. During this process, the flow of thought diverged into two main paths. Some participants immediately focused on "color," prioritizing the establishment of a variable structure for hypothesis verification. Others sought to find a context to interpret the hypothesis by immediately retrieving empirical knowledge or information encountered in their surroundings. Specifically, 13 of the 23 participants followed a "Variable Structure-Oriented Path (Path A in Fig. 2)," proceeding directly to the Construction of the Experimental Problem Space after problem recognition. Conversely, the remaining 10 exhibited a "Meaning-Oriented Path (Path B in Fig. 2)," attempting to secure problem-solving clues by exploring relevant experiences or knowledge before specifying variables; they prioritized the activation of prior knowledge.

P11: "My first thought was, 'How can honeybees distinguish colors?' ***Then I thought, 'Maybe they actually can.'*** *So, I felt a bit rushed to think about materials first, like* ***what kind of paper could be used to distinguish colors."***

P23: "First, ***I focused on the part about 'distinguishing colors,'*** *putting the honeybee aspect aside for a moment. I wondered, 'Do honeybees distinguish colors?' and suddenly remembered something my mother said. She told me that* ***if I wear yellow or bright clothes, bees would come towards me.*** *That remark just flashed through my mind."*

Thus, despite encountering the same hypothesis in the problem recognition stage, some participants attempted to frame the experiment by prioritizing variable structure, while others explored experimental possibilities by retrieving fragmentary knowledge from daily experiences or videos.

Construction of the Experimental Problem Space

After the problem recognition stage, participants explored the Experimental Problem Space by identifying the "color" factor as the independent variable and the "honeybee's color recognition" as the dependent variable. However, rather than mechanically constructing a comparative experiment by simply controlling non-color factors, they adopted an "exploratory approach strategy" to establish the preconditions for validity, thereby setting the basic frame of the experiment.

P9: "First, ***I thought different colored flowers were needed to distinguish colors,*** *so I listed the materials... Finally, I set up the experimental process* ***to observe the bees' movements*** *in an environment accessible to all [colors]."*

P13: "To certainly verify this hypothesis, I thought ***color must be the only differing condition***... ***Since bees follow flowers****, I placed flowers as rewards and applied differential rewards by color to see* ***if bees distinguish them."***

The statements from P9 and P13 indicate that they set "color" as the independent variable and "color recognition" as the dependent variable, intending to observe whether bees exhibited behavior confirming color distinction. Simultaneously, they demonstrated an awareness of the Control of Variables Strategy (CVS), recognizing that conditions other than color must be controlled, similar to Task 1. However, unlike Task 1, which was based on solid knowledge, they exhibited "intuitive variable control," determining the scope of control based on intuitive judgment in situations where the specific impact of variables was difficult to predict.

P7: "I'm not sure if sunlight should be a controlled variable... ***I just thought I should vary the lighting because that is the variable I want to observe****. I don't know if other conditions have an influence."*

*P16: "****I thought the flowers should be in the same state****. If they are different, [bees] might go to the better one...* ***so other than color, nothing should be different."***

Thus, the group that prioritized constructing the experimental problem space showed a consistent design pattern of setting color as the independent variable and recognition as the dependent variable. However, this process was not a deductive setting of variables, but an exploratory structuring process of identifying and controlling variables based on abductively constructed assumptions.

Strategic Use of Prior Knowledge for Hypothesis Testing Logic

Pre-service teachers explored appropriate cognitive resources (prior knowledge) to concretely fill the "variable structure" established in the previous stage. However, unlike Task 1, which had a clear standardized experimental model, Task 2 lacked a fixed procedure for hypothesis verification. Consequently, participants had to combine fragmented prior knowledge and experiences to devise independent verification logic regarding "by what principle will the honeybee's color distinction ability be proven?" The strategies emerging in this process were largely categorized into "Observation Strategy based on Empirical Preference" and "Conditioning Strategy borrowing General Science Principles." The former adopted "Innate Preference" as the core mechanism based on daily experiences or anecdotal knowledge. The latter established "Learning and Reward" as the operating principle by analogically applying general experimental principles learned in other fields (e.g., Pavlov's dog).

P1: "I recall learning somewhere—maybe not in school—that ***bees hate black****...* ***so if you wear black near a hive, it's dangerous.*** *Because of that knowledge, I thought they could probably distinguish colors."*

P8: "I remembered elders around me saying ***bees like bright clothes or yellow clothes****... So I wrote down clothes [as materials]."*

*P5: "****I could only think of looking for a difference like in Pavlov's dog experiment****... seeing the difference between when something is given and when it isn't. So I wrote about supplying honey or not."*

P14: "I wasn't sure how bees find flowers... I had some vague knowledge? ***Maybe they danced, or it was smell."***

These statements clearly illustrate the process by which pre-service teachers transformed incomplete knowledge resources into strategic ideas for experimental execution. Based on empirical episodes, P1 and P8 concretized the aforementioned "Observation Strategy based on Empirical Preference," constructing the core logic of the experiment on the assumption that "if they distinguish colors, they will move to the preferred color." Conversely, P5 borrowed the principles of classical conditioning from psychology to establish the "Conditioning Strategy borrowing General Science Principles." Through this, P5 derived a "behaviorist verification logic"—that "associating color (stimulus) and honey (reward) will result in behavioral change"—as the experimental design strategy. While some participants, like P14, remained in the memory retrieval stage without establishing a clear strategy, most attempted to conceive an experimental method by generating the most plausible mechanism within their available knowledge. This reflects both the limitations and the potential utility of prior knowledge in problem-solving.

However, this method construction was not a one-time event. It was supplemented whenever realistic constraints or new ideas emerged during the subsequent condition specification stage, exhibiting a cyclical flow of exploring alternatives based on prior knowledge or intuition. That is, the activation of prior knowledge and the conception of experimental methods developed interactively with the specification of experimental conditions.

Specification of Experimental Conditions and Development of the Experimental Design

Participants determined the experimental conditions for Task 2 in a relatively creative manner. Due to a lack of directly applicable experiences or knowledge, they developed experimental procedures by considering factors such as observability and feasibility. In this process, they gradually concretized variables and conditions by combining activated but limited knowledge (e.g., characteristics of bees or insects, animal experiment methods, color-related knowledge) or utilizing intuitive judgments to construct plausible explanations.

*P4: "I thought about poison because in my basic biology class, **we discussed poisonous mushrooms and how humans, if they survive a near-death experience with one, develop trauma and avoid it. I thought maybe honeybees are the same.**"*

*P6: "**I know bees definitely like flowers...** but I wasn't sure if they would just flock to honey or sugar water. And if **I just pasted colored paper on the wall, they might just move randomly without rules.** So, even though I wasn't fully confident, I switched to using flowers because **I had the idea that bees would prefer flowers over just colored paper.**"*

*P10: "I thought that to make the bees go there, **I should use something they like, so I considered flowers or drawings of flowers.** ... Also, **since red and purple are at the extremes of the color spectrum,** I decided on red and blue, which is close to purple, as they seemed like opposing colors."*

These statements reveal the cognitive patterns exhibited by pre-service teachers when establishing the "color" condition—the independent variable—during the specification of experimental conditions. P4 established a hypothesis by analogizing human learning principles (trauma) to bees—assuming a similar reaction (avoidance of poison)—and introduced flowers distinguished by the presence or absence of poison. P6 modified their initial idea (applying substances to colored paper) based on empirically acquired bee preferences and selected specific stimuli related to flowers. Similarly, P10 concretized experimental conditions by utilizing extreme values of the color spectrum to induce behavior. In these ways, participants inferred the most plausible conditions within the constraints of limited information.

During the condition-setting process, some participants could not clearly predict the results. Despite lacking confidence in the outcome (e.g., "I'm not sure what will happen"), they intentionally set conditions to ensure their tentatively predicted results would be most visible. A notable trend was the omission of "baseline control"—which verifies causality by checking reactions in the absence of the variable—in favor of immediately adopting conditions that could maximize the difference in expected effects.

P23: "When thinking of color, honey is generally yellow, ***so obviously yellow is the color to attract bees****. And I thought* ***black, which has no color, would be the opposite.*** *... I chose black because anyone would agree it's not bright."*

P11: "Because I heard bees can distinguish colors, I thought the hypothesis was likely true. So, I was rushed to think about what materials were needed to ***implement*** *this, like what kind of paper could distinguish colors."*

P23 omitted the comparison procedure with a neutral "non-colored group (achromatic)"—necessary for judging color recognition—and selected the "yellow vs. black" combination, believing it would reveal the most distinct difference. The cause of this design choice is further clarified in P11's statement. P11's use of the term "to implement" suggests that the pre-service teachers' thinking shifted from an attempt to neutrally verify a hypothesis to a process of exploring conditions that maximize differences to actually produce the predicted phenomenon. Consequently, instead of establishing sophisticated control groups or baseline controls, some participants adopted a strategy of immediately selecting combinations that would reveal the greatest expected effect as their experimental conditions.

Finally, regarding the method of measuring the dependent variable (honeybee color recognition ability), the focus was placed on the observability of reactions rather than the precision of hypothesis verification.

P13: "If they distinguish colors, ***there must be a case where they choose one specific color****. Since bees follow flowers,* ***I intended to place flowers as rewards and assign different rewards by color to see if they distinguish them****."*

*P15: "****Put black paper and white paper in a container, put several bees in, and observe where they go.*** *Wouldn't that show if they distinguish colors?"*

*P22: "****I would decorate the four sides [of a plastic container] with different colors.*** *I set up the experiment so that when bees are put in the entrance,* ***they can move to where they want.****"*

As indicated by these statements, many participants devised various methods to check results intuitively, such as directly observing the frequency of movement to specific colors (P15, P22) or inducing choice behavior via rewards (P13). Additionally, there were participants like P17, who intended to observe behavior in a scent-blocked space based on the certain belief that bees use scent, and P3, who proposed observing color distinction after imprinting the color red upon birth. In summary, although the experimental schemes varied among participants, an examination of their rationale reveals that all sought to complete their designs by selecting methods deemed most effective and certain for verifying the hypothesis within the bounds of their limited knowledge.

Review and Refinement of the Design

During the process of reviewing and refining their designs, participants actively utilized "mental simulation" to mentally rehearse the experimental procedure. Interview analysis revealed that the nature of these simulations varied by task. In Task 1, where prior knowledge was abundant, most participants reported visualizing a complete process, ranging from preparation and execution to anticipated results. Conversely, in Task 2, characterized by a lack of prior knowledge and difficult prediction, a significant number of participants stated they could only imagine the preparation and procedure, failing to clearly envision the final results due to uncertainty. However, this incomplete simulation and the consequent "reflective prediction" served as a catalyst for identifying potential design flaws and prompting modifications and supplements. The following statements illustrate how participants reconstructed their designs through mental simulation.

*P6: "**To see if they distinguish colors, I thought I needed something colored, so I initially wrote down colored paper.** But then **I thought bees wouldn't move much even if I put honey on the paper.** So, I decided, 'Let's use flowers instead,' and designed the next experiment."*

*P8: "Trying to experiment with just this (clothes)... I don't know bees well. **I thought the experiment might fail. So, I planned to do this first, and then supplement it (with an experiment using flowers).**"*

*P18: "**Initially, I thought of comparing red paper and blue paper to see where more bees would land**... but I felt that changed the nature of distinguishing color. I thought comparing **red paper and white paper would better determine if they can distinguish color**. Also, **I first planned to put honey on the paper** to see which one they ate from... but I realized the result might be due to something other than color distinction, so **I removed honey from the materials.**"*

These statements illustrate the diverse aspects of mental simulation. P6 anticipated issues with feasibility—that bees might not respond to colored paper—and devised "flowers" as an alternative. P8, considering the risk of failure with clothes alone, formulated a supplementary experiment. P18 went further, simulating not just the success of the experiment but the validity of result interpretation. Through reflective prediction, P18 identified that comparing different colors (red vs. blue) or introducing honey could compromise the hypothesis test. Consequently, P18 fundamentally modified the variables to enhance the logical completeness of the design.

The design review stage in Task 2 was not merely about correcting errors. It was a dynamic and recursive process where participants, amidst the uncertainty of result prediction, used mental simulation to foresee potential failures (P6), seek alternatives (P8), and secure logical validity (P18). Ultimately, participants concluded their designs by recording their confidence in the experiment's appropriateness and expected results through this review process.

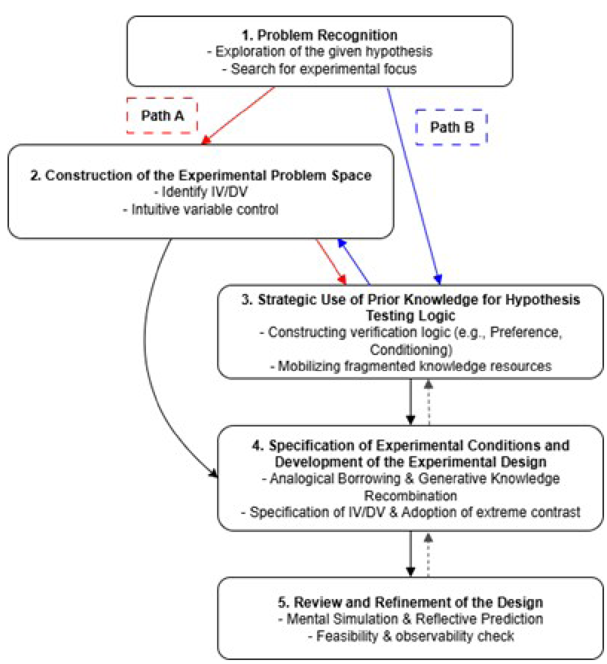

Fig. 2. The experimental design process of elementary school pre-service teachers as shown in task 2

The analysis derived the cognitive stages of pre-service teachers during Task 2. This process was not a simple linear flow but unfolded with stages repeatedly intersecting within an uncertain context. Participants attempted to secure design validity by combining and modifying limited prior knowledge. Fig. 2 schematically illustrates these typical cognitive stages.

The Role of Prior Knowledge and Abductive Reasoning in the Experimental Design Process

The analysis revealed that abductive reasoning appeared in both tasks but was notably more active in Task 2, where prior knowledge was scarce. This indicates that abductive reasoning is triggered to resolve uncertainty when learners are required to design experiments without solid background knowledge. Thus, abductive reasoning is not omnipresent; rather, it occurs selectively to bridge knowledge gaps and facilitate the progression of the design.

Abductive reasoning was classified into two major types based on the method of knowledge utilization and the nature of the output. First is the "Analogical Borrowing" type. This corresponds to "analogical abduction" as mentioned by Magnani (2001), involving the retrieval of similar experiences or knowledge to concretize conditions through one-to-one mapping. The core of this type is not importing the entire existing context, but extracting and transferring only specific properties necessary for problem-solving. For instance, in Task 1, P15 recalled a high school "pH concentration experiment" while designing the germination experiment. Despite the difference in topics, P15 borrowed the empirical property of "adjusting concentration by pouring liquid with a beaker" and adopted the beaker as a water control tool. This exemplifies the selective borrowing of the functional property (utility of the beaker) rather than the entire context of the past experience (pH experiment). Similarly, in Task 2, the selection of flowers as experimental materials was based on the property of knowledge that "bees like the sweetness of flowers." In summary, analogical borrowing manifested as a static reasoning pattern, directly applying specific properties identified in existing knowledge to determine specific experimental values without complex structural modification.

Second is the "Generative Knowledge Recombination" type. This can be viewed as an early form of "creative abduction," involving the fusion of knowledge or principles from different domains to construct a new causal mechanism. This type distinguishes itself from the first by going beyond simple attribute transfer; it combines multiple knowledge fragments to create a new experimental model when anomalies (limitations or potential failures) are recognized. A clear example is P5. Lacking knowledge of bee ecology, P5 borrowed the principle of "Pavlov's dog (classical conditioning)" from psychology and combined it with biological elements such as "honey (reward)" and "color (stimulus)." Through this, P5 generated a new hypothetical mechanism: "If trained on color, they will be able to distinguish it." Similarly, P13 went beyond merely placing flowers by applying the principle of "behavioral reinforcement via reward" to devise a complex structure involving flowers and sugar water. In essence, knowledge recombination manifested as dynamic reconstruction, organizing heterogeneous knowledge and principles to create novel solutions.

Abductive reasoning in the experimental design process was closely linked to the process of prior knowledge activation. "Direct Application," where accurately known knowledge is reproduced exactly, can be distinguished as a case where abductive reasoning is not utilized. When pre-service teachers applied learned concepts or classroom knowledge directly, inference to resolve uncertainty was unnecessary. Therefore, while direct application is a form of utilizing prior knowledge, it does not fall within the category of abductive reasoning. In contrast, "Analogical Borrowing" and "Generative Knowledge Recombination" necessitated abductive reasoning due to the fragmentary or uncertain nature of the activated knowledge. Consequently, Analogical Borrowing served a complementary function of filling gaps in the design, whereas Generative Knowledge Recombination contributed to exploring new possibilities and constructing creative solutions.

Discussion

This study conducted an in-depth exploration of the cognitive processes exhibited by pre-service elementary teachers during experimental design tasks. The results indicate that their thought flow was structured into five major stages, with distinct cognitive characteristics and patterns of prior knowledge utilization depending on the task type.

First, in Task 1, participants possessed sufficient prior knowledge and clearly recognized the variables of the hypothesis. Immediately after recognizing the problem situation, they rapidly recalled relevant prior knowledge and established the basic structure of the experiment by clearly defining independent, dependent, and control variables. This process resembled a linear flow of thought, directly applying recalled knowledge to specify experimental conditions and review logical validity. This aligns with Kalyuga's (2007) view that learners with high prior knowledge can quickly structure problem situations and construct valid strategies. It also supports existing literature suggesting that prior knowledge positively influences the inquiry process (Garcia-Carmona et al., 2017; Hailikari et al., 2008; Von Aufschnaiter & Von Aufschnaiter, 2007). However, even in Task 1, some pre-service teachers remained uncertain about specific details (e.g., amount of water, germination period). In such cases, they selectively applied plant-growing experiences or intuitively chose elements deemed appropriate for the context. This can be viewed as an instance of selective abduction (Magnani, 2005), where existing knowledge is not merely reproduced but utilized to fit specific variables. Thus, abductive reasoning intervened even when prior knowledge was generally sufficient, specifically to address remaining uncertainties in specific conditions.

Conversely, in Task 2, participants lacked prior knowledge and perceived the variable structure of the hypothesis as ambiguous, leading to an exploratory thinking process. Due to the absence of direct prior knowledge, they faced difficulties in initial variable setting and attempted to combine limited resources by mobilizing background knowledge about honeybees, daily life experiences, and knowledge from non-science domains. Notably, participants explored new possibilities and constructed alternative explanations or experimental conditions when existing knowledge was insufficient to explain the phenomenon. This can be understood as an instance of creative abduction (Magnani, 2005). The knowledge mobilized in this process shared similar characteristics with the variables the reasoner sought to determine, resembling analogical reasoning, where explanations are constructed through similar experiences (Magnani, 2005). This flow of thought was not strictly linear but exhibited recursive characteristics, returning to previous stages as needed. This parallels findings by Zhou et al. (2016), who reported that inexperienced learners tend to perform manipulations inconsistent with experimental goals or include unnecessary variables, and aligns with Manlove et al. (2006), who noted that learners generally struggle with constructing experiments due to unsystematic planning. This demonstrates that not only the quantity of knowledge but also its contextual appropriateness and the quality of thinking strategies significantly impact the experimental design process (McElhaney & Linn, 2011).

Through in-depth analysis, it was observed that pre-service teachers shifted their fundamental design goals and selected corresponding approaches based on task familiarity and result predictability. In Task 2, where predicting results was difficult due to a lack of prior knowledge, some participants designed experiments suitable for implementing a desired outcome rather than verifying causality. In other words, compared to Task 1, participants in Task 2 approached the design with an "engineering goal" (outcome implementation) rather than a "scientific goal" (hypothesis verification). This shift can be understood through the essential difference between scientific inquiry and engineering design: science aims to construct knowledge to understand the natural world and identify causal relationships, while engineering aims to develop solutions or implement results (Lewis, 2006; Schauble et al., 1991). As Zimmerman (2005) noted that inquiry strategies may vary depending on experimental goals and expectations, pre-service teachers appeared to reconstruct their inquiry goals in a pragmatic direction to establish criteria for judging hypotheses amidst the difficulty of prediction. Interestingly, this change in thought process closely mirrors the problem-solving methods of expert engineers. Lim (2009) reported that expert engineers exhibit a relatively linear inquiry process when solving "causal problems" (similar to the scientific goal in this study) but a cyclical design process when solving "methodological problems" (similar to the engineering goal). This suggests that the strategic shift shown by pre-service teachers is not merely a manifestation of immaturity, but a sophisticated adaptive process of flexibly changing cognitive frameworks according to problem types, much like experts.

This shift in inquiry goals specifically influenced the function of abductive reasoning and the structure of the experiment. In Task 1, which pursued a "scientific goal," most participants devised comparative experiments including baseline controls. Here, selective abduction performed a complementary function, resolving uncertainties to stabilize the design while controlling detailed variables to strictly verify causality. In contrast, some participants in Task 2, who established an "engineering goal," focused on solving the problem of "How can the honeybee's color-distinguishing behavior be revealed?" rather than verifying the scientific question through causality. This goal shift led to the omission of neutral control groups without color (baseline controls) in the experimental structure. Their primary concern was not neutrally verifying the effect of color presence (e.g., yellow vs. gray) but contrasting two conditions expected to induce the most distinct behavioral differences (e.g., yellow vs. black). Creative abduction was actively utilized in the process of intentionally creating conditions to make phenotypic differences distinct. However, the engineering approach in Task 2 does not imply an absence of scientific thinking. According to Purzer et al. (2015), learners deeply connect scientific concepts and design only when analyzing trade-offs to find optimal solutions among alternatives. The pre-service teachers' deliberation on "which color to select" mirrors this trade-off analysis, suggesting the potential for scientific thinking to emerge through creative abduction within complex decision-making processes.

Furthermore, this study confirmed that abductive reasoning, previously discussed mainly in the hypothesis generation stage, plays a pivotal role throughout the entire experimental design process. As Paavola (2004) noted, abduction is a goal-oriented activity that predicts phenomena or seeks answers within the constraints of existing background theories. In this study, pre-service teachers' abductive reasoning functioned as a strategy to advance the design to achieve the goals of either "hypothesis verification" or "outcome implementation."

In conclusion, pre-service teachers flexibly shifted design goals according to the problem situation and selectively utilized appropriate abductive reasoning. The transition to engineering design and the abductive reasoning process observed in unfamiliar tasks partially resonate with the arguments of Nersessian (2025) and Clement (2022), who posit that scientists integrate diverse cognitive resources while modifying and applying existing strategies to create new models. Thus, the design process of pre-service teachers should not be viewed merely as an immature attempt, but as part of an expert inquiry strategy to resolve uncertainty and expand the possibilities of discovery. However, this flexible strategy of learners poses an important question for current science education. Chinn and Malhotra (2002) pointed out that many school science inquiries are biased toward pragmatic goals like "making the right answer" or "producing an effect" rather than actual scientific reasoning, which may lead students to develop distorted perceptions of the nature of science. The fact that pre-service teachers prioritized familiar pragmatic approaches in uncertain situations underscores the importance of providing opportunities for students to experience a balance between authentic scientific inquiry and pragmatic problem-solving in schools. Therefore, this study emphasizes the need to understand learners' utilization of cognitive resources more sophisticatedly in inquiry-based learning and to support them in exercising inquiry strategies appropriate to the context.

Conclusion Implications

This study investigated the cognitive processes involved in pre-service elementary teachers' experimental design and elucidated how abductive reasoning manifests according to prior knowledge and task characteristics. The conclusions derived from the findings are as follows.

First, the experimental design process of pre-service teachers exhibited a five-stage cognitive flow: (1) Problem Recognition, (2) Construction of the Experimental Problem Space, (3) Strategic Use of Prior Knowledge for Hypothesis Testing Logic, (4) Specification of Experimental Conditions and Development of the Experimental Design, and (5) Review and Refinement of the Design. However, the fundamental goals and approaches diverged based on task familiarity and result predictability. In tasks where prior knowledge was abundant and results were predictable, participants primarily pursued a "scientific goal" aimed at logically verifying hypotheses. Conversely, in unfamiliar tasks where prediction was difficult, some participants shifted toward a "engineering goal" with a pragmatic orientation, focusing on implementing observable phenomena. This demonstrates that experimental design is not a rigid adherence to a single framework but a strategic process that adapts flexibly to the problem context.

Second, the shift in design goals accompanied a change in the functional role of abductive reasoning. Under the "scientific goal," selective abduction functioned primarily as a complementary mechanism to reinforce existing frameworks and stabilize the design. However, under the transition to the "engineering goal," creative abduction was actively utilized as a generative mechanism to break through uncertainty and devise new conditions. Thus, abductive reasoning proved to be a sophisticated strategic thinking process where roles and functions vary according to design goals, rather than merely filling knowledge gaps.

These findings offer the following implications for promoting and supporting learners' abductive reasoning in inquiry-based learning.

First, this study expands the scope of abductive reasoning—previously discussed mainly in the hypothesis generation stage—to the entire experimental design process. This suggests that educators should guide students to perceive experimental design not merely as a procedural activity applying existing knowledge, but as a creative and dynamic cognitive activity for problem-solving.

Second, the results provide specific implications for educational approaches to cultivating scientific design competencies. Familiar tasks (like Task 1) allow for the application of prior knowledge but limit the experience of "creative abduction" required to seek new solutions in uncertain situations. Conversely, unfamiliar tasks (like Task 2) can effectively trigger creative abduction but may lead some learners to construct designs biased toward practical goals, omitting basic controls. Therefore, science educators need to employ pedagogical strategies that intentionally present unfamiliar and uncertain problem situations while providing sophisticated support. This ensures that students do not stop at practical problem-solving but proceed to apply core scientific design principles, such as variable control, while engaging in creative reasoning.

Finally, this study has limitations regarding generalizability as it is a qualitative inquiry involving 23 pre-service teachers from a specific university of education. Additionally, the analysis of cognitive processes relying on self-reported interview data may diverge from actual thinking processes. Future research should expand the participant pool to include pre-service teachers from diverse backgrounds. Furthermore, quantitative analyses of experimental design processes or intervention studies verifying the effectiveness of instructional strategies to promote abductive reasoning are necessary.

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Conflicts of Interest

The author(s) declared no conflicts of interest.

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