

Bridging the novice-expert gap: The role of inhibitory control and interventions in overcoming buoyancy misconceptions

Yushan Xiong,^{1,2} Jialan Liu,¹ Jiejie Lai,¹ Tongyi Zheng,¹ Xuhuai Qu,¹ Qiuye Li¹,¹ Yi Zhong,^{1,2} Lei Bao^{1,3,*} and Shaona Zhou^{1,2,†}

¹Guangdong Provincial Key Laboratory of Quantum Engineering and Quantum Materials, National Demonstration Center for Experimental Physics Education, School of Physics, South China Normal University, Guangzhou, People's Republic of China

²National Research Center for Educational Materials (Elementary and Middle School Physics Materials Research), Guangdong Basic Research Center of Excellence for Structure and Fundamental Interactions of Matter, Key Laboratory of Atomic and Subatomic Structure and Quantum Control (Ministry of Education), South China Normal University, Guangzhou, People's Republic of China

³School of Biological Science and Medical Engineering, Research Center for Learning Science, Key Laboratory of Child Development and Learning Science (Ministry of Education), Southeast University, Nanjing, People's Republic of China



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This study investigates the cognitive processes of novice students in science learning, with a specific focus on how inhibitory control is employed to overcome a common student misconception about the buoyant force in liquid, which leads to the belief that “the greater the depth an object is in a liquid, the greater the buoyant force it experiences.” Utilizing a negative priming paradigm integrated with eye-tracking technology, the research examines the role of inhibitory control in facilitating conceptual change among novice learners. The findings reveal that successful problem-solving in novices is contingent not only on the acquisition of scientific knowledge but also on the effective activation of inhibitory control over misconceptions. A repeated measures analysis of variance (ANOVA) demonstrated significant effects of student expertise levels and experimental conditions on reaction times, with novices exhibiting significantly longer reaction times compared to experts, indicative of lower inhibitory control ability. However, following targeted intervention, novices' average reaction times progressively decreased, approaching those of experts, suggesting an improvement in inhibitory control. Additionally, eye movement data analysis revealed distinct differences in information processing strategies between novice and expert students. Novices frequently engaged in reviewing and comparing information across multiple areas during problem solving, whereas experts exhibited more efficient information processing, rapidly identifying and suppressing misconceptions. The eye-tracking data provided further insights into the cognitive processes and behavioral patterns of novices across different intervention phases, highlighting the dynamic interplay between inhibitory control and conceptual learning. These findings underscore the critical role of inhibitory control in overcoming misconceptions and offer implications for the design of targeted instructional interventions.

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I. INTRODUCTION

In a world increasingly shaped by science and technology, fostering scientific literacy requires students to develop deep, meaningful understandings of key concepts. Since the 1980s,

research in science education has revealed a critical insight: students come to the classroom with preexisting ideas, or preconceptions, that influence how they interpret new information. These intuitive beliefs often clash with scientific principles, creating barriers to learning. Traditional teaching methods, which focus on delivering information rather than engaging with students' thinking, often fail to address these misconceptions. As a result, even after instruction, students may struggle to apply scientific concepts accurately in real-world contexts. This competition between intuitive thinking and scientific understanding highlights a central challenge for educators, which requires designing learning experiences that actively reshape students' conceptual frameworks to

*Contact author: lei.bao@outlook.com

†Contact author: zhou.shaona@m.scnu.edu.cn

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effectively transition from their preexisting beliefs toward deeper understandings of scientific concepts.

Existing literature has demonstrated that naïve preconceptions or misconceptions are often deeply ingrained and resistant to change through traditional teaching methods [1]. This leads to the need to critically examine how preconceptions interact with scientific concepts and to understand the nature of conceptual change. Recent empirical studies in science education have indicated that individuals may retain misconceptions even after extensive instruction [2–4]. These misconceptions can coexist with scientific knowledge, creating cognitive competitions and conflicts that hinder students' reasoning and problem-solving abilities.

To better understand the coexistence and competition between scientific concepts and misconceptions at the behavioral level, researchers have employed a range of methods, including reaction time measurements and psychophysiological techniques such as functional magnetic resonance imaging (fMRI) and electroencephalography [5]. These studies have revealed the significance of inhibitory control in overcoming misconceptions during conceptual change [6,7]. The negative priming (NP) paradigm, which was originally proposed by Tipper to explore the critical role of inhibition in selective attention, has been shown to be an effective experimental approach that has been used in previous studies on inhibitory control in previous studies [8,9]. The findings suggest that educators should develop effective teaching strategies to help students effectively inhibit intuitive misconceptions in science learning and problem solving.

In the domain of physics education, a prevalent depth-buoyancy misconception holds that “greater depth leads to greater buoyancy” [10], a notion that directly contradicts the Archimedes principle. This study seeks to apply the negative priming (NP) paradigm to investigate whether inhibitory control plays a role in overcoming this misconception when solving buoyancy problems involving depth-related interference. Specifically, an intervention was designed to examine changes in the degree of inhibitory control engagement among novices as they solve buoyancy problems. By comparing novice performance in NP experiments before and after the intervention, this study aims to uncover how inhibitory control contributes to the different cognitive processes in conceptual change.

II. LITERATURE REVIEW

A. Inhibitory control and the negative priming paradigm

In the process of science learning, misconceptions often act as cognitive barriers that need to be addressed in instruction. Inhibitory control is part of the ability to resist automatic responses, temptations, distractions, or interference, and to resolve conflicting situations [11]. Studies

have shown that when adults correctly respond to counter-intuitive scientific questions, brain regions associated with error monitoring and inhibitory control show increased activation. This increased activity is particularly evident when correct answers are provided to compete with students' naïve conceptions, highlighting the critical role of inhibitory control in addressing misconceptions [7,12]. This phenomenon aligns with the inhibitory control model, which posits that individuals can draw upon both heuristic and analytical thinking at any given moment, with these two cognitive modes in constant competition. Typically, heuristics prevail due to their efficiency. However, when heuristics conflict with the scientific content of a problem, they may lead to nonscientific solutions. In such instances, individuals must engage the inhibitory control mechanism to override incorrect responses and initiate a more analytical reasoning approach [9,13]. Consequently, inhibitory control plays a crucial role in scientific reasoning by enabling individuals to suppress intuitive naïve conceptions in favor of scientific ones [6,8,14,15].

Existing studies on the inhibitory control model using the negative priming (NP) paradigm have demonstrated that individuals require inhibitory control in the learning of scientific problem solving [6,7]. The NP paradigm typically employs two conditions: a test condition and a control condition. In each condition, assessment items are grouped into pairs of prime-and-probe items. Participants are required to complete the prime item first, followed by the probe item. In the test condition, the prime item is designed to present a counterintuitive stimulus that conflicts with an intuitive strategy or misconception. To answer correctly, participants must inhibit this intuitive strategy when responding to the prime item. The probe item, on the other hand, aligns with the intuitive strategy, meaning it can be answered correctly by either relying on the intuitive conception or applying the correct scientific concept. In the control condition, the prime item is designed with a neutral stimulus that does not activate or interfere with the intuitive strategy. The probe item in the control condition is identical to the one in the test condition and aligns with the intuitive strategy.

The logic of the NP paradigm is as follows: In the test condition, participants inhibit the intuitive strategy when completing the prime item. When they subsequently encounter the probe item, they need to reactivate the intuitive strategy, which results in longer reaction times for the probe item. In the control condition, however, the neutral prime item does not require the inhibition of the intuitive strategy. Therefore, participants can directly apply the intuitive strategy to the probe item, leading to shorter reaction times. A negative priming effect (NP effect) is observed when the reaction time for probe items in the test condition is significantly longer than that in the control condition. This effect reflects the inhibition of the intuitive strategy during the prime item and its subsequent reactivation during the

probe item, providing evidence for the involvement of inhibitory control processes [16–18].

B. Understanding students' learning mechanisms of science concepts

Over the past two decades, numerous studies have examined the differences in physics conceptual understanding between experts and novices, congruently showing that experts develop a more advanced and integrated knowledge structure [19,20]. Neurocognitive research has further revealed that experts exhibit distinct brain activation patterns compared to novices, particularly in regions associated with inhibitory control [21,22]. For instance, Masson *et al.* compared the brain activation patterns of physics undergraduates (with at least five college-level physics courses) and arts and humanities undergraduates (with no formal physics background) during a task involving the assessment of simple circuit diagrams to identify “single line” infantile ideas. The results indicated that physics undergraduates exhibited significantly greater activity in brain regions linked to inhibitory control, suggesting that the development of expertise is closely tied to enhanced inhibitory control mechanisms [23]. Similarly, Dunbar *et al.* investigated brain activity differences between experts and novices while processing Newtonian physics concepts. Their findings revealed that although novices could often select correct answers, their depth of conceptual understanding markedly differed from that of experts, highlighting a fundamental gap in the cognitive processing of scientific concepts [24]. Together, these studies underscore the significant differences in conceptual understanding between novices and experts, emphasizing the critical role of inhibitory control in conceptual development.

Existing research has also explored interventions that promote an individual's inhibitory control capability. Babai [25] conducted a study to obtain the reaction time of 84 sixth graders' understanding of perimeters, with some receiving a warning intervention and others not. The results indicated that under incongruent conditions, accuracy was significantly higher in the warning group, and reaction times were notably longer in all conditions compared to the control group. This suggests that the explicit warning activated the inhibitory control mechanism, enabling the students to overcome interference. The findings imply that students' problem-solving skills can be enhanced through simple and targeted interventions that specifically alert them to the potential pitfalls of the task. An fMRI study conducted by Nenciovici *et al.* [26] further investigated the effects of instructional interventions on novice conceptual understanding. By addressing misconceptions in electrical and mechanical concepts among undergraduate students and analyzing corresponding changes in brain activity, the study found that during error correction, brain regions associated with memory retrieval and monitoring were more active than those linked to inhibitory control. While

these findings offer valuable insights into intervention strategies, further research is needed to develop systematic approaches for enhancing the inhibitory control efficiency of novices.

Understanding the mechanisms underlying the learning of scientific concepts requires examining not only learning outcomes but also the cognitive processes involved, such as an individual's attentional focus. The eye-mind hypothesis posits a strong correlation between eye movements and attentional allocation, suggesting that eye movements can serve as a proxy for cognitive engagement [27]. Eye-tracking technology, which captures detailed records of eye movements, provides an objective means of assessing attentional distribution and has been widely utilized across diverse research domains, including reading [28], information processing [29], and human-computer interactions [30]. In the context of science learning, eye-tracking has been extensively applied in education research on mathematics [31], physics [32], and chemistry [33]. By offering insights into the allocation of attention during cognitive tasks, this technology enables researchers to explore differences in attentional patterns between novices and experts as they engage with scientific concepts. Such investigations can shed light on the developmental trajectory of students' inhibitory control, providing a deeper understanding of how scientific conceptual understandings are acquired and refined.

C. The current study

In recent years, an increasing number of researchers have devoted themselves to the study of subject-based expert students, aiming to help those with academic difficulties transform into expert learners [34]. Among them, an increasing number of studies focus on the differences between experts and novices in problem solving [35]. With the development of cognitive psychology, researchers have found that the problem-solving ability of experts is far better than that of novices, so their learning methods and strategies have some lessons for novices. Although studies have established the role of inhibitory control in overcoming misconceptions [6,7,13], the mechanism by which inhibitory control affects novice learners' conceptual change remains underexplored. Second, most interventions focus on conceptual knowledge acquisition but lack explicit training to suppress intuitive false concepts to help students improve the efficiency of inhibitory control [25,26].

In the field of physics education, numerous studies have indicated that certain students' misconceptions can be attributed to the primitive thinking of an intuitive rule “more A leads to more B,” which is referred to as Ohm's p-prim in the knowledge in pieces theory of conceptual understanding [36]. Aligned to this category, Murphy and Unal's research revealed a common misconception about buoyancy, where students believe that “larger or heavier objects sink more” [37,38]. When first learning the concept of buoyancy, many students often develop related incorrect

preconceptions [39,39]. Common misconceptions include the beliefs that “weight determines whether an object will sink or float,” “volume alone dictates an object’s buoyancy,” and “greater depth leads to greater buoyancy” [38,40]. Students may incorrectly associate the mass of an object with its depth, assuming that an object at a shallower depth has a smaller mass and, consequently, experiences reduced buoyancy. This misconception reflects a lack of understanding of the fundamental principle that buoyancy is determined by the volume of displaced fluid and is unrelated to depth [10]. In this study, we focus on the depth-buoyancy misconception that believes “greater depth leads to greater buoyancy,” which is likely stemmed from the p-prim of “more A (deeper) leads to more B (greater)” [41]. Students may observe that the deeper an object goes underwater, the more force it seems to require to bring it up, leading them to incorrectly infer that depth directly affects buoyancy.

The present study employs the negative priming (NP) paradigm to investigate whether novice and expert students need to activate the inhibitory control function when solving buoyancy problems involving competition or interference from the depth-buoyancy misconception. Further, the study examines the performance differences between novice and expert students in NP experiments before and after intervention.

To investigate the above research aims, we designed a task in which participants judged which of two fish in a tank experiences greater buoyancy. The fish vary in size (volume) and depth, creating four item types: congruent (aligned with the misconception), incongruent and very incongruent (conflicting with the misconception), and neutral (no depth interference). The NP paradigm involves two conditions: a test condition, where participants complete an incongruent or very incongruent prime item followed by a congruent probe item, and a control condition, where participants complete a neutral prime item followed by a congruent probe item. The logic of the NP paradigm is that if participants inhibit the misconception during the incongruent prime, reactivating it for the congruent probe becomes harder, resulting in longer reaction times or reduced accuracy (the NP effect). If the depth-buoyancy misconception and its inhibitory control are valid, then in this study’s task, performance on congruent probe items following incongruent or very incongruent prime items would be worse than performance on congruent probe items following neutral prime items, as evidenced by lower accuracy or longer reaction times.

In addition to behavioral measures, we employ eye-tracking technology to capture participants’ attentional patterns during the task. Areas of interest (AOIs) include fish depth labels, size labels, and schematic diagrams. By analyzing fixation duration, saccadic paths, and revisits to AOIs, we aim to identify how novices allocate attention to depth versus volume cues before and after intervention.

The study also incorporates a two-stage intervention designed to enhance both conceptual understanding and inhibitory control efficiency. The first stage focuses on teaching Archimedes’ principle and providing volume-focused examples, while the second stage emphasizes practice in suppressing depth interference through mixed item types. By comparing novices’ performance before and after the intervention, we aim to uncover how inhibitory control contributes to conceptual change and problem-solving efficiency.

III. DESIGN AND METHODOLOGY

A. Participants

A priori power analysis was performed to ensure that the study had sufficient statistical power. The G*Power was employed in this study. In the analysis of variance (ANOVA) designed within three groups involving neutral, incongruent, and very incongruent prime types, it is determined that a minimum of 28 participants in each group would be required to detect a medium effect size of 0.25 and to reach 80% power at a significance criterion of $\alpha = 0.05$. We recruited 98 participants from a medium-high ranking normal university in China. The participants included 45 first-year and second-year undergraduate physics students majoring in physics (25 women and 20 men; average age = 19 ± 1.3 years), and 53 first-year and second-year undergraduate liberal arts students majoring in literature (30 women and 23 men; average age = 19 ± 2 years). All participants were right-handed, native Chinese speakers, with normal or corrected-to-normal vision and no color blindness. The 45 physics students were in the degree program for future physics teachers and were considered experts. The liberal arts students only had middle school-level education on buoyancy concepts without any college physics and were considered novices. In addition, it is found that 100% of novices show the depth-buoyancy misconception through interviews.

B. Method and materials

The experiment topics are selected from the junior high school physics textbook, which is compiled in accordance with the national curriculum standards (reference Ministry of Education of the People’s Republic of China). The experimental material presents a scenario featuring two different-sized fish in the same tank, a large one and a small one, each occupying a different location in the tank, simultaneously. The reason for choosing fish as the object of judgment is that they can swim freely in the water, thereby evoking the potential interference of depth on the perception of buoyancy. This often leads students to believe that “greater depth leads to greater buoyancy.” Participants were asked to determine which fish experienced greater buoyancy based on their size and depth in the water. Participants responded by pressing the right button on the trackpad with their right index finger if they believed the

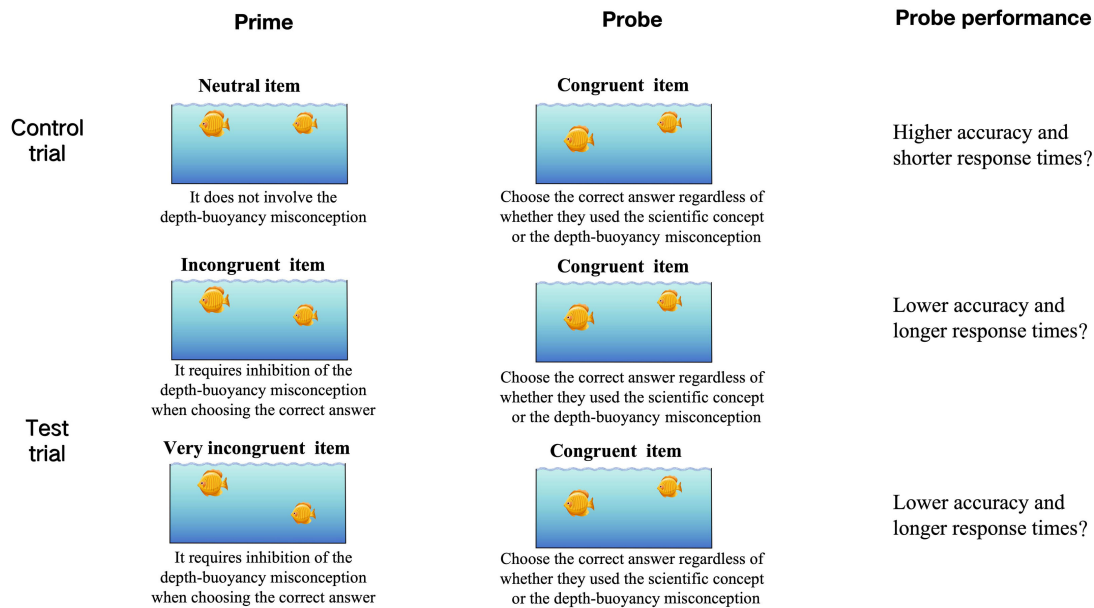


FIG. 1. The negative priming (NP) paradigm adaptation of the “greater depth leads to greater buoyancy” task.

fish on the right was more buoyant. They pressed the left button with their left index finger if they chose the fish on the left.

The NP paradigm lies in the fact that if the depth-buoyancy misconception has been suppressed in a previous process, it becomes more difficult to reactivate it in the present process, compared to the condition that it was not previously suppressed. This generally manifests as an increase in reaction time or a decrease in accuracy, constituting a negative priming effect [6]. By comparing negative priming effects under different experimental conditions, one can infer the involvement of inhibitory control mechanisms [20,21]. As shown in Fig. 1, the neutral items were designed with two fish of different sizes at the same depth. This context does not present a difference in depth, and therefore, is not likely to cue the depth-buoyancy misconception. The incongruent and highly incongruent questions were designed with settings involving a large fish at a small depth and a small fish at a greater depth, with the highly incongruent items exhibiting larger differences in depth between the two fish. In this case, the explicit differences in depth are likely to trigger the depth-buoyancy

misconception, which will produce answers in conflict with those based on the scientific concept. Therefore, in order to correctly answer these questions, the inhibition of the misconception is needed. For the highly incongruent items, the misconception can be more pronounced and may require stronger inhibitory control. In contrast, the congruent items were designed with settings involving a large fish at a greater depth and a small fish at a smaller depth, allowing participants to answer correctly regardless of whether they relied on the depth-buoyancy misconception or the correct scientific concept. Therefore, no inhibitory control is required to answer these questions correctly.

The present study set up three different depth types and three different volume types of fish, each with a ratio of 1:1.5:2. For each NP experiment, a total of 36 test items were used. These included 6 neutral items, 6 incongruent items, 6 highly incongruent items, and 18 congruent items. To balance the sequential effects between experimental conditions and possible habituation reactions, the presentation order of the 36 prime-probe pairs was completely randomized. As shown in Table I, there are three experimental conditions: control, test, and filler. The filler

TABLE I. The design of the six conditions of prime-probe pairs in the current study.

Condition	Prime item	Probe item	Number of items
Control trial	Neutral	Congruent	6
Test trial	Test 1 Incongruent	Congruent	6
	Test 2 Very incongruent	Congruent	6
Filler trial	Neutral	Very incongruent	6
	Incongruent	Very incongruent	6
	Very incongruent	Very incongruent	6

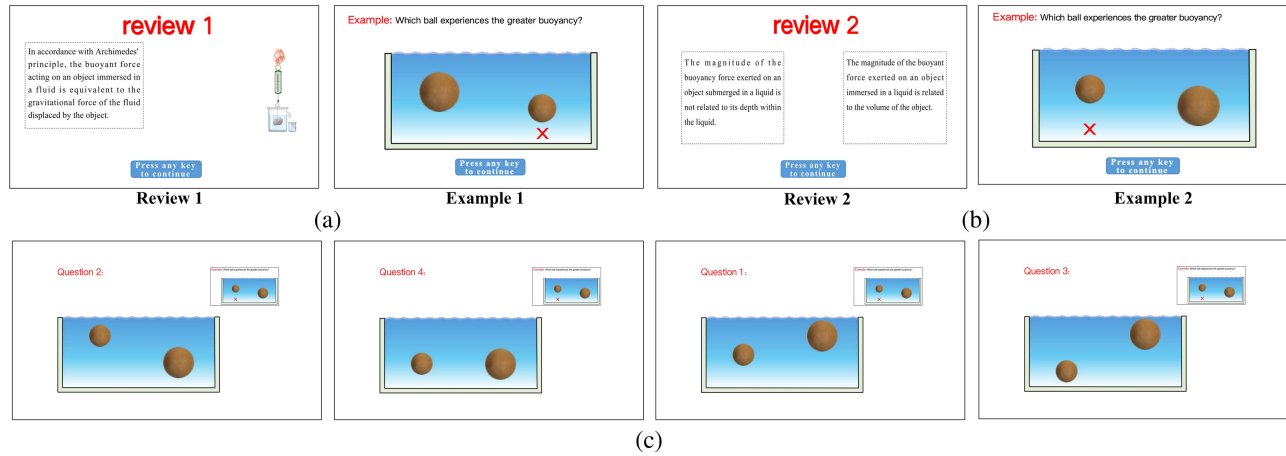


FIG. 2. Three sections of two interventions: review, example, and training questions. For each intervention, the training encompasses congruent, neutral, incongruent and very incongruent items. (a) The first intervention. (b) The second intervention. (c) Training questions.

condition was designed to conceal the main purpose of the experiment and balance the responses to the probe items. Data from the filler condition were not included in the data analysis.

As shown in Fig. 2, the review in the first intervention provides a description of Archimedes' principle and a schematic diagram of the experimental operation, enabling students to comprehend the method for judging the magnitude of buoyancy. The example section shows a pair of wooden balls with different depths and volumes. This example is designed to help students focus on the volume of the objects rather than their depth when determining which ball experiences greater buoyancy. By doing so, it reduces the reliance on situational memory and encourages the use of the correct scientific principle. In the second intervention, review 2 concentrates on the methodology for assessing the strength of buoyancy, with a particular emphasis on circumventing deep interference. The sample and training questions follow those in the first intervention. After each intervention and example, four training questions are presented, encompassing congruent, neutral, incongruent, and very incongruent items, with the objective of enhancing students' understanding and proficiency in assessing buoyancy forces. These training questions are positioned in the lower left corner of the screen, while scaled-down sample questions appear on the upper right side of the screen, facilitating students' review of their reasoning and assessment of their understanding of the buoyancy concept. In the second intervention, review 2 concentrates on the methodology for assessing the strength of buoyancy, with a particular emphasis on circumventing deep interference. The sample and training questions follow the same format as those in the first intervention.

Eye-tracking technology was employed in this study to provide insights into the attentional processes and cognitive strategies used by novice and expert students during the

experimental tasks. By monitoring eye movements, we aimed to understand how students allocate their attention to different elements of the experimental stimuli and how this allocation changes with different experimental conditions and interventions. The experimental interface was divided into predefined areas of interest (AOIs) to facilitate the analysis of eye movement data. For the NP experiment, the screen was divided into two main AOIs: AOI 1 (left area) and AOI 2 (right area), corresponding to the two fish in the experimental scenario. These AOIs were designed to capture participants' attention allocation between the two objects being compared. In the intervention sections, additional AOIs were defined based on the content of the review, examples, and training questions. For instance, during the review section, AOI 1 was designated for the textual description of Archimedes' principle, and AOI 2 for the accompanying schematic illustration.

C. Procedure

General instructions were first given orally to the participants by the person in charge of data collection. Each participant sat approximately 70 cm in front of a laptop in a classroom seat. Before each task began, the same instructions were again provided visually on the computer screen.

As shown in Fig. 3, expert participants participated in only one negative priming (NP) experiment. Novice participants were first subjected to the first NP experiment to assess whether they were influenced by the misconception that greater depth leads to greater buoyancy. The review stage introduces Archimedes' principle to aid in understanding the science of buoyancy. Following the completion of intervention 1, the novices will perform the second NP experiment to test the effectiveness of the intervention. In this stage of the intervention, emphasis is placed on the method of judging buoyancy, particularly the significance

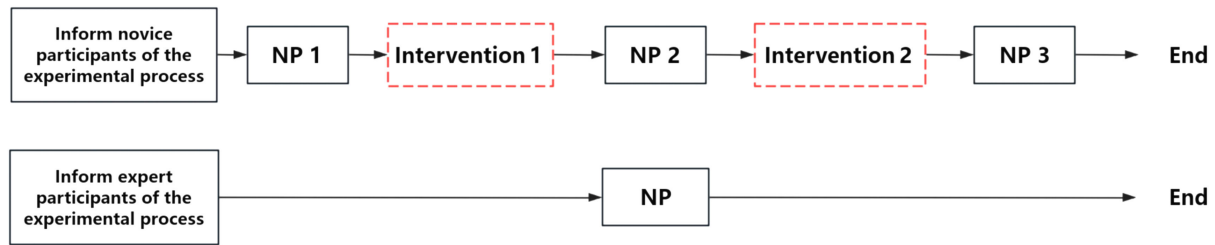


FIG. 3. Experimental procedure.

of avoiding the influence of depth. At the end of intervention 2, the novices will conduct the third NP experiment to further evaluate their understanding of buoyancy.

The NP experiment in the experimental program mirrored the original NP paradigm, with participants tasked to evaluate pairs of items under both test and control conditions. For each item, participants were instructed to identify which of the two fish appeared to be experiencing more buoyancy. Participants pressed the right button on the trackpad with their right index finger if they believed the fish on the right was more buoyant, and similarly, pressed the left button with their left index finger if they chose the fish on the left. Before embarking on the actual task, participants completed a series of 12 practice trials to acquaint themselves with the visual stimuli, the trial flow, and the response mechanics. Throughout the practice and experimental sessions, no participant requested further clarification or showed any sign of confusion, even when prompted to review.

Figure 4 shows the basic flow of the NP experiment. Each trial began with the presentation of a fixation cross for 500 ms, followed by a prime item (which could be neutral, incongruent, or very incongruent). Once the participant provided an answer, a fixation cross was displayed for 500 ms, followed by a probe item (which was a congruent question). After the participant provided an answer to the probe, a fixation cross was displayed for 500 ms, followed by a visual mask for 1000 ms. The mean accuracies (ACCs) and reaction times (RTs) of both the prime and probe were recorded, respectively.

The whole experiment was carried out on a laptop computer using E-prime 3.0 software. The negative priming (NP) paradigm was applied to explore students' inhibitory control, and both ACCs and RTs were obtained in the measurement [42,43]. In addition, the EYESO EX90 eye-tracking device was also used to record participants' eye movements for a deeper understanding of the students' learning process. The eye-tracking device has a high sampling rate and is able to accurately capture the participants' visual attention processes. It is connected to a high-resolution laptop computer and fixed beneath the computer monitor for data acquisition. During the experiment, participants were allowed to move their heads and eyes freely and respond to tasks using a keyboard. EYESO STUDIO software was used to record and analyze eye movement data, while EV screen recording software was utilized to record experimental screens for further detailed analysis.

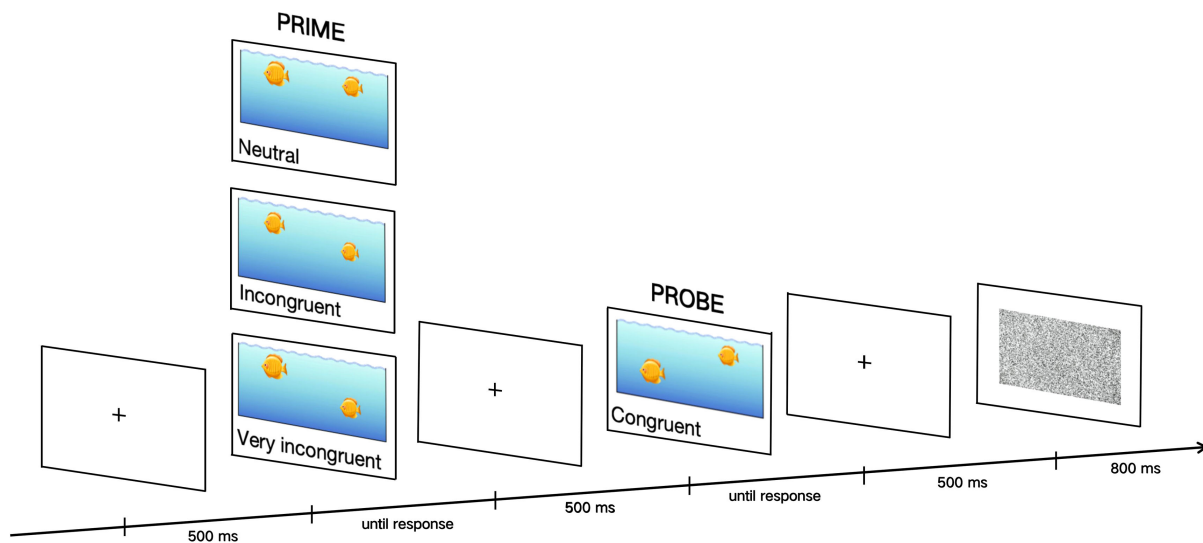


FIG. 4. The procedure of the NP experiment.

D. Data analysis

The study labeled the data from the first, second, and third NP experiments of novice students as novice 1, novice 2, and novice 3, to study the development of novice students' performances. The filler trials were employed to conceal the main purpose of the experiment and to equilibrate the distribution of correct and incorrect responses to the probe items. Consequently, the analysis excluded the data from these filler trials, focusing solely on the data obtained from the control and test trials. In the control trials, the prime-probe pairs were designed to be neutral and congruent items. In the test trials, test 1 prime-probe pairs are incongruent-congruent items, and test 2 prime-probe pairs are very incongruent-congruent items. SPSS 26.0 was utilized for the data analysis. To compare the differences between novice and expert students, a repeated measures ANOVA with a 2 (subject group: expert vs novice 1) $\times$ 3 (experimental condition: control, test 1, test 2) design was employed. To investigate the changes in novice students' performance before and after the intervention, a repeated measures ANOVA with a 3 (subject group: novice 1, novice 2, novice 3) $\times$ 3 (experimental condition: control, test 1, test 2) design was conducted. For both repeated measures ANOVAs, the within-subjects variable was the experimental condition, and the dependent variables were the mean ACCs and RTs of the subjects to the probe items (congruent item) under both conditions. Finally, to compare the differences between novice students after intervention and expert students, a 2 (subject group: expert vs novice 2) $\times$ 3 (experimental condition: control vs test 1 vs test 2) repeated measures ANOVA was conducted. Additionally, a 2 (subject group: expert vs novice 3) $\times$ 3 (experimental condition: control vs test 1 vs test 2) repeated measures ANOVA was performed to compare novice 2 and novice 3 with experts.

The eye-tracking data were analyzed using EYESO STUDIO software. Fixation durations were the primary metrics used to assess participants' attentional focus and cognitive processing. The fixation duration was calculated for each AOI to determine the amount of time participants spent focusing on specific areas of the screen. Independent

samples t tests were conducted to compare the metrics between the novice group and expert group, thereby verifying the differences in attention allocation and information processing strategies between the two groups. Furthermore, the influence of the intervention on the information processing ability of novices was explored by analyzing the changes in their eye movement behavior during the two intervention processes.

IV. RESULTS

A. ACCs and RTs of novice and expert students

The negative priming effect can manifest only when subjects accurately solve the incongruent or highly incongruent prime item. Therefore, only the ACCs and RTs of the probe with the correct prime answer are calculated. Subjects with a correct rate for the incongruent problem below 50% (inclusive) were excluded from the analysis, and data points exceeding the average reaction time across all problem types were deleted. After these exclusions, the remaining data set includes 61 students: 31 novice students and 30 expert students. The mean ACCs and RTs for the detection items are presented in Table II.

1. Differences in ACCs and RTs between novice and expert students

Taking the accuracy (ACC) of probe items as the dependent variable, a 2 (subject group: expert vs novice 1) $\times$ 3 (trial condition: control vs test 1 vs test 2) repeated measures ANOVA was conducted. The main effect of the subject group was significant ($F = 27.243$, $p < 0.001$, $\eta^2 = 0.316$), indicating significant differences in ACC between experts and novices. However, the main effect of experimental conditions was not significant ($F = 1.328$, $p > 0.05$, $\eta^2 = 0.022$), meaning that changes in experimental conditions did not significantly affect students' overall ACC. Furthermore, the interaction between the subject group and experimental conditions was not significant ($F = 1.848$, $p > 0.05$, $\eta^2 = 0.030$), indicating that both experts and novices maintained stable performance across different experimental conditions.

TABLE II. The mean accuracies (ACCs) and reaction times (RTs) of the novice group and expert group on probe ($M \pm SD$). Note that novice 1/2/3 denotes the novice group of students ($N = 31$) conducting the first/second/third NP experiment.

Group	Accuracy (ACC) on probe			Reaction times (RT) in ms on probe		
	Control	Test 1	Test 2	Control	Test 1	Test 2
	Neutral prime	Incongruent prime	Very incongruent prime	Neutral prime	Incongruent prime	Very incongruent prime
Expert	0.98 ± 0.05	0.99 ± 0.03	0.99 ± 0.04	849.86 ± 309.58	921.37 ± 337.02	1025.96 ± 418.71
Novice 1	0.73 ± 0.32	0.69 ± 0.32	0.66 ± 0.36	1788.01 ± 839.47	2393.93 ± 1091.24	2665.94 ± 1420.5
Novice 2	0.80 ± 0.30	0.79 ± 0.31	0.76 ± 0.34	1141.33 ± 669.63	1370.65 ± 874.73	1271.66 ± 735.46
Novice 3	0.95 ± 0.10	0.96 ± 0.09	0.96 ± 0.09	807.14 ± 233.13	853.25 ± 295.00	851.19 ± 304.20

Using the probe item response time (RT) as the dependent variable, the main effect of the subject group was significant ($F = 57.849$, $p < 0.001$, $\eta^2 = 0.495$), indicating a difference in the RT between experts and novices. The main effect of the experimental condition was also significant ($F = 14.397$, $p < 0.001$, $\eta^2 = 0.332$), showing that the RT varied across experimental conditions. The interaction between the subject group and the experimental condition was significant ($F = 77.601$, $p < 0.001$, $\eta^2 = 0.086$). Further simple effect analysis was conducted to explore the differences in RT across the three experimental conditions. Specifically, the RTs on probe items were analyzed and compared between the novice group and the expert group under control, test 1, and test 2 conditions. The results showed no significant difference in RT between the three experimental conditions for experts ($p > 0.05$), indicating that no negative priming effect was detected. Novices exhibited significantly longer RT under test conditions compared to the control condition ($p < 0.001$), further supporting the existence of a negative priming effect specific to the novice group.

2. The differences between novice students' ACCs and RTs before and after intervention

A design of 3 (subject group: novice 1 vs novice 2 vs novice 3) $\times$ 3 (trial condition: control vs test 1 vs test 2) repeated measures ANOVA was conducted. In terms of ACC, the main effect of the subject group was significant ($F = 9.038$, $p < 0.001$, $\eta^2 = 0.167$), suggesting that the intervention positively impacted the accuracy of novice students. However, neither the main effect of experimental conditions ($F = 1.301$, $p > 0.05$, $\eta^2 = 0.028$) nor the interaction between the subject group and experimental conditions ($F = 0.677$, $p > 0.05$, $\eta^2 = 0.015$) was significant, indicating that the improvement in accuracy was attributed to the intervention and was not influenced by the experimental conditions.

In terms of reaction time (RT), the main effect of the subject group was significant ($F = 40.253$, $p < 0.001$, $\eta^2 = 0.472$), indicating that the RTs varied significantly across the three stages for novice students. Specifically, compared to preintervention novice students, the RTs of novice 2 and novice 3 were significantly shorter, indicating an improvement in response speed after the intervention. Additionally, the main effect of experimental conditions ($F = 9.533$, $p < 0.001$, $\eta^2 = 0.096$) and the interaction between the subject group and the experimental condition ($F = 4.914$, $p < 0.01$, $\eta^2 = 0.098$) were also significant. Further simple effects analysis revealed that, while the RTs of preintervention novice students varied significantly across experimental conditions, this effect was not significant in novice 2 ($p > 0.05$) and novice 3 ($p > 0.05$). These results suggested that the intervention mitigated the influence of experimental conditions on RT.

3. Differences in ACCs and RTs between novice students after intervention and expert students

A repeated measures ANOVA was conducted with the ACC of probe items as the dependent variable, using a 2 (subject group: expert vs novice 2) $\times$ 3 (trial condition: control vs test 1 vs test 2) design. The interaction between subject group and trial condition was not significant ($F = 0.756$, $p > 0.05$, $\eta^2 = 0.013$), indicating that both experts and novices exhibited stable ACC across different trial conditions. The analysis revealed a significant main effect of subject group ($F = 14.053$, $p < 0.001$, $\eta^2 = 0.192$), indicating that the ACC of experts was higher than that of novice 2. When considering the RT on probe items as the dependent variable, the interaction between subject group and trial condition was also not significant ($F = 1.011$, $p > 0.05$, $\eta^2 = 0.017$), suggesting that both groups maintained consistent RT across different trial conditions. The main effect of subject group was significant ($F = 6.71$, $p < 0.05$, $\eta^2 = 0.102$), indicating that the RT of experts was shorter than that of novice 2.

A repeated measures ANOVA was performed with the ACC of probe items as the dependent variable, using a 2 (subject group: expert vs novice 3) $\times$ 3 (trial condition: control vs test 1 vs test 2) design. The interaction between subject group and trial condition was not significant ($F = 2.745$, $p > 0.05$, $\eta^2 = 0.044$), indicating that both experts and novices maintained stable ACC across different trial conditions. The main effect of subject group was not significant ($F = 1.635$, $p > 0.05$, $\eta^2 = 0.027$), suggesting that novice 3 had reached a similar ACC comparable to experts after two intervention cycles. Finally, when the RT on probe items was used as the dependent variable, the interaction between subject group and trial condition was not significant ($F = 0.047$, $p > 0.05$, $\eta^2 = 0.001$), suggesting that both groups maintained stable RT across different trial conditions. The main effect of subject group revealed a small but detectable group difference ($F = 4.148$, $p = 0.046$, $\eta^2 = 0.066$), with novice 3 having a slightly shorter RT than the experts.

B. Eye movement behaviors of novice and expert students

1. Data specification

Eye-tracking technology is an effective tool to detect the time, location, and content of gaze for an eye over a short period. Eye movement data are typically converted into eye movement metrics for further analysis, such as fixation duration, fixation counts, pupil size, fixation duration proportion, saccade counts, and scan path. These metrics reflect the distribution of attention, the order of fixations, and other aspects. Fixations and saccades are fundamental measures for describing eye movements and together form the scan path. Fixations represent the visual focus on a specific point in the field of vision. Fixation duration is the

TABLE III. Independent sample T-test results of each average return visit between the novice group and the expert group. Note that AOI 1 is the left area of interest and AOI 2 is the right area of interest.

	Novice ($N = 31$)	Expert ($N = 30$)	t	p	Cohen's d
	$M \pm SD$	$M \pm SD$			
Average number of revisits in NP experiment	96.94 $\pm$ 57.73	36.13 $\pm$ 15.39	5.58	<0.001	1.43
Number of revisits in AOI 1	49.06 $\pm$ 28.29	16.97 $\pm$ 8.04	5.98	<0.001	1.53
Number of revisits in AOI 2	47.87 $\pm$ 30.45	19.17 $\pm$ 8.78	4.97	<0.001	1.27

total time a participant spends fixating on a given area of interest (AOI), indicating the level of attention. In the present study, the average fixation time is calculated for specific AOIs of each item during preintervention, two interventions, and three NP experiments. Refixations refer to the situation in which the eye leaves an AOI and then returns to it, indicating the reprocessing of previously viewed information. The number of refixations was also calculated in the study.

The study used independent samples t tests to compare differences in eye movement indices between novices and experts and to calculate the effect size. The analysis explored the differences in student performance in the NP experiments and the effect of interventions, and how the eye movement behaviors reflect differences in students' inhibitory control abilities.

2. Differences in eye movement behaviors between experts versus novices

A series of independent sample t tests was used to compare the differences in eye movement indices between the expert group and the novice group, as shown in Table III. First, the difference in the number of revisits between novices and experts was analyzed. The left and right areas in question are divided into area 1 of interest (AOI 1) and area 2 of interest (AOI 2). These AOIs were defined to capture participants' attention allocation between the two fish in the experimental scenario. The left area (AOI 1) and the right area (AOI 2) were chosen to reflect the spatial arrangement of the fish in the tank, allowing us to analyze how participants' gaze shifted

between the two objects being compared. In the negative priming (NP) experiment, there was a significant difference in the average number of revisits between novices and experts ($t = 5.48$, $p < 0.001$, Cohen's $d = 1.14$). Novices ($M = 96.87$, $SD = 58.71$) had more return visits than experts ($M = 36.13$, $SD = 15.39$), indicating that novices constantly shifted their attention more to reviewing and comparing information between different AOIs. In addition, Fig. 5 visually demonstrates the differences in gaze behavior between a typical expert and a typical novice when completing the NP experiment through eye tracking. In Fig. 5, the circle represents the position of eye fixation, the size of the circle represents the fixation time, the solid line connecting the continuous fixation points represents the saccade path, and different AOIs are marked with black rectangular boxes, which further confirms the significant differences in attention allocation and task processing strategies between the two groups.

3. Comparison of two intervention sessions for novices

An intervention process consists of three sections: review, example, and training questions. The eye movement behavior of novices under different intervention conditions was investigated by analyzing the fixation time of their eye movements. The results from these sections are illustrated in Fig. 6, which provides a comprehensive overview of how novices allocate their attention and process information across the two interventions.

- (1) Review: In the review sections of both interventions, areas of interest (AOIs) were divided into left and right zones to capture how novices allocate their

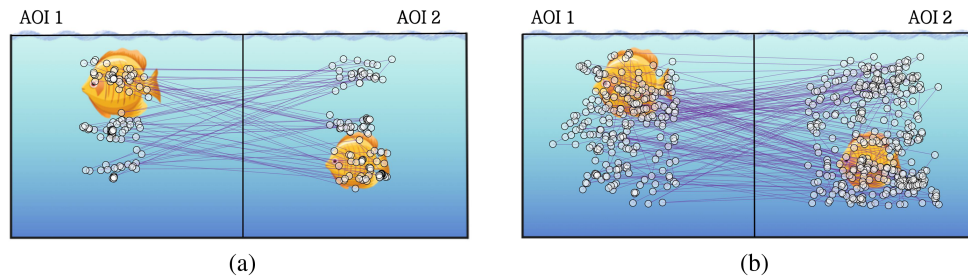


FIG. 5. Eye movements of a typical expert and a typical novice completing an NP experiment. (a) Eye movement distribution of a typical expert. (b) Eye movement distribution of a typical novice. Circle: where the eyes are focused; number of circles: gaze time; solid line connecting continuous gaze: saccade; different AOIs are marked with black rectangles.



FIG. 6. Student attention on different AOIs in both intervention 1 and intervention 2. Circles with numbers represent the fixation time on each AOI. (a) Review (intervention 1), (b) review (intervention 2), (c) example (intervention 1), (d) example (intervention 2), (e) training questions (intervention 1), (f) training questions (intervention 2).

attention between different types of information. In the first intervention [Fig. 6(a)], AOI 1 was designated for the textual description, and AOI 2 for the accompanying picture. The eye movement scan paths showed that novices' fixation time in AOI 1 (text) was more than twice that of AOI 2 (picture), suggesting that they found the text more challenging to understand or required more time to process the textual information. In contrast, the second intervention [Fig. 6(b)] focused on the methodology for assessing the magnitude of buoyant force, with the review section divided into left and right interest zones. Here, fixation times on AOI 1 and AOI 2 were more balanced, indicating that novices were able to process information more evenly. This change suggests that after the first intervention, novices

had gained a better understanding of Archimedes' principle, allowing them to identify and process key information more quickly and efficiently.

- (2) Example: For the example sections, the areas of interest (AOIs) were divided differently in the two interventions. In the first intervention [Fig. 6(c)], the AOIs were divided into three regions: text (AOI 1), problem statement (AOI 2), and experimental diagram (AOI 3). The eye movement data revealed that novices spent a significant amount of time processing these examples, as evidenced by longer fixation durations. This suggests that the exposure to the material required more cognitive effort and time to understand the principles. In the second intervention [Fig. 6(d)], the AOI was divided into a text section (AOI 1) and a topic section (AOI 2). Fixation

durations were shorter, indicating that novices were able to comprehend the problems more quickly. This improvement suggests that the novices had gained a better understanding of the material after the first intervention, allowing them to process the examples more efficiently.

- (3) Training: The training items were identical in both interventions, with an example attached to the upper right corner of each [Figs. 6(e) and 6(f)]. The AOIs were divided into two regions: AOI 1 for the problem and AOI 2 for the example question. The eye movement fixation observed during the training sessions showed that novices relied more heavily on the example during the first intervention. In contrast, during the second intervention, the fixation times on the example decreased, indicating a more profound grasp of the knowledge in the training section. This suggests that novices had a deeper understanding of the material, leading to decreased dependence on the examples provided.

V. DISCUSSION

The present study designed and conducted negative priming (NP) experiments to demonstrate the key role that inhibitory control plays in helping novices overcome the depth-buoyancy misconception. For the expert-level students, the reaction times of probe items in the text trial did not increase significantly when compared to the control trial, and there was no NP effect. The results indicate no presence of inhibitory control, suggesting that the depth-buoyancy misconception was not activated among experts. This is consistent with the research conclusions of Zhu *et al.* [44], Foisy *et al.* [45], and Versteeg *et al.* [46]. This may be because the strong scientific ability of experts leads to no significant difference in the behavioral data of probe items under different prime items. The participants in the expert group were undergraduate physics majors with a strong understanding of the concept of buoyancy.

For the novice group, reaction times in probe items under the test trial were significantly higher compared to those in the control trial, confirming the existence of a negative priming (NP) effect. This result is consistent with previous studies, in which inhibition of misconception is often associated with longer reaction times [40,42]. The results suggest that inhibitory control is involved in overcoming the depth-buoyancy misconception. This may be because misconceptions are deeply rooted in long-term memory and can be activated even after scientific learning to compete with the scientific concepts during learning [43]. Therefore, the application of scientific knowledge must suppress this interference. Although novice participants in this study have learned the scientific method to determine buoyancy in junior high school, they still have the depth-buoyancy misconception. This is consistent with the inhibitory control model, which assumes that cognitive development involves

acquiring complex concepts and suppressing previously learned incorrect knowledge and skills. Although individuals possess the necessary knowledge and skills, they may still make mistakes in solving problems due to the failure of inhibitory control over intuitive strategies. This does not imply a lack of the correct knowledge and skills, but rather indicates the critical role of inhibitory control in conceptual development [47–50]. In light of this outcome, teachers should design exercises to guide students in identifying and suppressing competing misconceptions. In addition, students should develop self-monitoring skills, which can be encouraged through the practice of reflecting on their thought processes through self-assessment.

After the intervention, the novice students seemed to have significantly improved their inhibitory control. A possible reason is that the first intervention introduced scientific perspectives, triggering cognitive conflict and enhancing students' ability to detect errors. During subsequent training, students applied the scientific method, laying the foundation for improved efficiency. Research indicates that frequent use of the scientific method can elevate its importance and potentially alter students' conceptual understanding [51,52]. The second intervention directly refuted the misconception, which may have activated students' misconceptions but also facilitated their conceptual transformation [53–56]. These two interventions led to significant decreases in novice students' reaction times during the negative priming experiment, indicating an enhancement of their inhibitory control ability. A further *t* test on the data revealed that after the first intervention, novices' ACCs and RTs in detection tasks were still significantly different from those of experts. After the second intervention, novices' ACCs and RTs in problem solving approached the expert level. The results can provide useful insights for teaching practices. Teachers can present scientific concepts clearly in various forms, using charts, models, videos, and other resources to aid instruction.

Additionally, by comparing eye movement indices between expert and novice groups, the study revealed that novices had a significantly higher average number of refixations in the negative priming experiment than experts. This suggests that novices more frequently revisit and compare information across various areas of interest when tackling problems, potentially indicating more back-and-forth comparisons in their cognitive activities [57]. These cognitive processes can be further elucidated by analyzing eye movement scan paths. The eye-tracking data indicated that novices' visual attention frequently shifted as they examined the two fish, suggesting ongoing examination and comparison of information in the task. Conversely, experts' scan paths were more streamlined, suggesting more efficient information processing with less time spent rereading or reexamining information. The significant differences in average refixations and scan paths between novices and experts highlight how visual attention is

allocated during problem solving. This disparity may be linked to their respective abilities to exert inhibitory control, particularly when addressing buoyancy problems with complex interference. Novices might require more visual scrutiny to override the competitive intuitive responses, whereas experts can more effectively suppress these responses and directly process critical information [58]. These insights are crucial for educational practice, suggesting that educators should consider strategies to enhance novices' inhibitory control abilities, thereby improving the efficiency of problem solving.

VI. CONCLUSIONS

This work emphasized the exploration of three questions. First, it explored whether inhibitory control involves overcoming the depth-buoyancy misconception. Second, it investigated changes in novice students' performance in the NP experiment following interventions. Third, it analyzed differences in behavior and eye movements between novices and experts during problem solving after interventions. The present study demonstrates that inhibitory control interventions effectively help overcome the depth-buoyancy misconception. Findings indicate that interventions can significantly enhance learning outcomes and facilitate a quicker grasp of buoyancy concepts. This underscores the importance of targeted interventions in science education to foster cognitive development. After two interventions, novices' performance approached that of experts, indicating that novices can rapidly enhance their inhibitory control over false concepts and potentially reach expert levels through effective educational interventions. This convergence highlights the potential of educational strategies to accelerate students' cognitive development.

Research indicates that even experts with advanced scientific knowledge may retain early misconceptions [59], suggesting that fundamental conceptual changes over time do not always overcome initial misconceptions. This insight prompts educators to reconsider their approach to science education. Rather than attempting to completely eradicate these misconceptions, which are deeply ingrained in students' long-term memory, educators should help students become aware of these conflicts and acknowledge their

tenacity. By highlighting the distinction between intuition-based attitudes or behaviors and those grounded in scientific principles, teachers can foster a more profound understanding of scientific concepts [60]. Consequently, the role of targeted educational strategies in scientific learning is especially significant. Specifically, fostering the development of inhibitory control is crucial when students encounter concepts that clash with their preexisting beliefs. Educators should craft and apply strategies that empower students to monitor and manage their intuitive responses conflicting with scientific principles. Such interventions can enhance students' capacity to address scientific problems effectively and cultivate a deeper comprehension of scientific knowledge.

However, there are some limitations in this study. As the research is centered on a specific misconception, its findings may not be generalizable to all intuitive concepts or scientific learning in general. Furthermore, the prevalence of different misconceptions can vary with age, suggesting that the ease of dispelling these misconceptions may differ among individuals. Consequently, further research is necessary to explore the development trajectories of other intuitive concepts and how they can be effectively addressed across various age groups.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available because they contain sensitive personal information. The data are available from the authors upon reasonable request.

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