Inhibitory control involvement in overcoming the position-velocity indiscrimination misconception among college physics majors

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Students hold a variety of initial (mis)conceptions that are inconsistent with scientific knowledge and hinder their physics learning. The initial (mis)conceptions could coexist with the scientific ones, even after a conceptual change. Inhibitory control may help overcome initial (mis)conceptions. This study investigated if and how inhibitory control can overcome position-velocity indiscrimination (PVI), a common kinematics misconception. We designed a negative priming paradigm with various prime-probe item pairs. College physics majors had to judge if the items describing the instant that two locomotives have the same velocity were correct. When congruent probes (same position-same velocity) were followed by incongruent primes (same position-different velocity), participants performed worse than when neutral primes (i.e., not passing points) were presented beforehand. The result verified a typical negative priming effect, indicating that inhibitory control is involved in overcoming the PVI misconception. Congruent probes preceded by incongruent primes implicitly triggering the PVI misperception had a lower negative priming effect than explicitly activating it. The results indicated that inhibitory control was needed to overcome the PVI misconception, and the explicit activation of the misconception required more inhibitory control.

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I. INTRODUCTION

Extensive previous research has demonstrated that students hold a variety of initial (mis)conceptions that are inconsistent with scientific ones [1]. These initial (mis) conceptions would pose obstacles to teaching and learning scientific concepts in physics at all education levels, from kindergarten to college [2,3]. Several conceptual change models have been proposed to represent the learning pathways from students' initial naïve conceptions to the science ones [4], which can be classified into two main categories, i.e., the initial conceptions no longer exist vs still exist after a conceptual change [5]. Nonetheless, a growing body of research supports the hypothesis that initial (mis)conceptions and scientific conceptions coexist [6–9].

Recent behavioral and neurocognitive investigations have further shown that when task performance necessitates the employment of a less intuitive but more scientific conception rather than an appealing but incorrect naïve idea, inhibitory control functions are activated, even in experts [5,10–15]. Inhibitory control refers to controlling one's attention, behavior, thoughts, and/or emotions to override a strong internal predisposition or external lure [16]. Specifically, inhibitory control of attention enables individuals to suppress prepotent mental representations, including resisting proactive interference from initial (mis) conceptions acquired earlier. Thus, the inhibitory control function has been suggested as having a potentially crucial role in the conceptual change process, as it helps students

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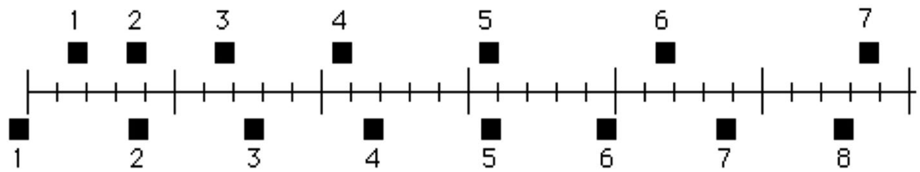
19. The positions of two blocks at successive 0.20-second time intervals are represented by the numbered squares in the figure below. The blocks are moving toward the right.



Do the blocks ever have the same speed?
(A) No.
(B) Yes, at instant 2.
(C) Yes, at instant 5.
(D) Yes, at instants 2 and 5.
(E) Yes, at some time during the interval 3 to 4.

FIG. 1. Item 19 from the 1995 version of FCI. This item was developed to assess students' ability to discriminate velocity from position. Options B, C, and D are distractors for students because the two blocks are in the same position at instants 2 and 5. Students may not be able to discriminate between the velocity and position of an object, which represents an initial misconception in kinematics, i.e., "position-velocity indiscrimination".

avoid being distracted by initial (mis)conceptions [5,10–15]. When students become aware that their initial (mis)conceptions are no longer tenable, they experience cognitive dissonance or dissatisfaction, which leads to the process of conceptual change [17–19]. The resolution of this cognitive dissonance or interference, which can be a top-down inhibition of the initial (mis)conception, can rapidly restore processing capacity to apply scientific ones [20–22].

In physics education, a large number of previous studies have investigated students' initial (mis)conceptions of kinematics [23–27]. Specifically, Hestenes *et al.* argued that "the typical commonsense concept of motion is vague and undifferentiated" [24] (p. 143). In Hestenes *et al.'s* 1995 version of the Force Concept Inventory (FCI), item 19 can be considered a prototypical example for probing such a commonsense belief, which indicates a confounded understanding of position and velocity, defined as "position-velocity indiscrimination" (PVI) (see Fig. 1). Students holding this (mis)conception can be attracted by the distractors describing that the blocks at the same location would have the same speed, i.e., instant(s) 2 and/or 5 in the example shown in Fig. 1.

It is worth noting that Hestenes *et al.* claimed that students' commonsense beliefs about motion (including the PVI misconception) are theorylike and have been seriously advocated by leading intellectuals in pre-Newtonian times [28]. However, it does not mean that the existence of such a misconception is opposed to the claims that students' knowledge is fragmented, as proposed by other models [29–31]. Specifically, Stavy and Tirosh's intuitive rule "*Same A-Same B*" may account for the PVI misconception. The intuitive rule may be activated by specific external task features, for example, the instant that two objects are in the same position, which leads to a wrong conclusion, i.e., "*Same A* (position)-*Same B* (velocity)" [32]. Thus, the PVI misconception can be attributed to students incorrectly employing the intuitive rule "Same A-Same B" as the solution strategy.

As evidenced by previous studies, this indiscrimination of position velocity is present in adolescents and college students [24–27]. However, it remains unclear whether and how inhibition control plays a role in overcoming the initial PVI idea when processing Item 19 or items like it (referred to as the PVI-type questions) in learning kinematics. Hence, the primary goal of this study is to determine the extent to which inhibition of the PVI initial (mis)conception may help college physics students answer PVI-type questions correctly. Specifically, the current study adopted the negative priming (NP) paradigm to explore the involvement of inhibitory control in solving PVI-type questions. The NP paradigm is an effective paradigm that has been used in previous studies on inhibitory control [5,11]. The primary logic of the paradigm is that if a misconception is inhibited in a preceding process, the reactivation of the misconception during the present process would be more difficult than when it is not inhibited in the preceding process, which would present a slower or less accurate response (referred to as an NP effect). By comparing the NP effects among different experimental conditions, researchers could further infer how the inhibitory control may be involved in different cognitive processes.

II. LITERATURE REVIEW

A. The coexistence of initial (mis)conceptions and scientific conceptions

A growing interest in understanding students' misconceptions has led to many studies on conceptual change. Conceptual change can be defined as "learning pathways from students' pre-instructional conceptions to the science concepts to be learned" [1]. To date, more than 86 distinct models have been proposed to explain the process underlying conceptual change [4]. These theoretical models hold different assumptions about why these misconceptions exist and what the main barriers to conceptual change are [33].

Among the frequently mentioned models, some researchers argued that, after a conceptual change, the existing misconceptions must be replaced by more adequate and scientifically accurate ideas [1,19,34–36]. For example, Vosniadous' framework of mental model theory assumes that students' knowledge structures represent relatively coherent organizations of knowledge [37]. When exposed to the scientific explanations of a physical phenomenon that violate intuitive ideas, students' existing conceptual structures required radical reorganization rather than just an enrichment process of simply adding new information [38]. The model postulates implicitly that conceptual change requires significant reorganizing of students' preexisting knowledge structures and that the targeted naïve idea is utterly abandoned or no longer exists in its initial form [39,40].

This replacement perspective, however, has long been criticized and overtaken by a more complex systems view of knowledge, in which students' intuitions are considered resources for cognitive growth or conceptual change [41]. During conceptual change, these cognitive recourses, such as phenomenological primitive (*p* prim) [29,42,43] and intuitive rules [31], must be integrated and organized into a knowledge system to gain the capacity to employ the proper recourse correctly in any given context.

In diSessa's model of "knowledge in pieces (KiP)" [29,30], *p* prims are small fragmentary casual relationships from the naïve sense of mechanisms in intuitive physics, which may work in typical contexts of use but always fail in other contexts, hence the misconceptions expressed. Kip viewed knowledge as a complex system of many types of elements, including *p* prims, and viewed conceptual change as a reorganization of *p* prims into a larger knowledge system [29,42,43]. Specifically, "Elements need to be re-contextualized, not erased, and many coordinated changes are necessary to create normative scientific concepts" [42] (p. 44). In this case, the knowledge system after the conceptual change may have many common elements similar to the one before the change but with different organization [43]. Accordingly, *p* prims related to misconceptions should be developed and refined rather than replaced [29].

Similarly, Stavy and Tirosh assumed that learners' misconceptions are often established by underlying intuitive rules [31]. Learners frequently exhibit similar intuitive responses to a variety of scientific and daily tasks that share some external characteristics. Then, learners' misconceptions may emerge when intuitive rules are inappropriately used in these tasks. A common incorrect intuitive response, for example, claiming that "the heavier the object is, the faster it falls," can be attributed to misusing the intuitive rule "*More A* (heavier)-*More B* (faster)," cued by an object's external features of mass or volume [44]. Like the *p* prims in diSessa's model, these intuitive rules that lead to misconceptions are not extinguished even after a conceptual change occurs, but rather they arise when the rules are applied in inappropriate circumstances.

Recently, there has been a growing consensus on the coexistence of initial (mis)conceptions and scientific conceptions [6–9]. For example, Solomon's model suggests that when students learn to differentiate and move fluently between two contrasting domains of knowledge, the scientific domain and the life-world domain, conceptual change occurs [45]. Consequently, misconceptions originating from the real-world domain are not eradicated by such a conceptual change. In a newer model that Ohlsson proposed, he made it clear that two alternative conceptions about a target domain can exist at the same time: one is the resident conception about the target domain and the other is a conception about another domain that is also being applied to make sense of the target domain [8]. When the cognitive utility of one conception is implicitly evaluated over another through a stage called "competitive evaluation," it becomes the dominant conception in the target domain. More recent research has also shown that scientific knowledge can surpass misconceptions after a conceptual change but does not supplant them [9,46].

The idea of coexistence suggests employing instructional strategies other than the cognitive conflict method, which was often mentioned as an effective way toward conceptual change (e.g., Strike and Posner's "classical conceptual change approach") [6,9,19,31,47–51]. For example, Potvin's prevalence model suggested three teaching conditions to be fulfilled, which included (i) the availability of the programmed (desired) scientific conception, (ii) the installation of inhibitive "stop signs" for obtaining the correct recognition of particular contexts where they lead to errors, and (iii) the durable prevalence of the programmed scientific conception. Accordingly, the model indicates that an increase in the prevalence of a scientific conception will surpass its related initial (mis)conception [9].

Furthermore, the conceptual change process may recruit inhibitory control to facilitate the selection of contextually appropriate scientific conceptions while inhibiting initial intuitive and inappropriate conceptions sorted in the long-term memory [6,52]. In the next section, we will discuss the inhibitory control's function in the conceptual change in detail.

B. Inhibitory control in physics conceptual learning and problem solving

Executive function (also called executive control or cognitive control) refers to the "general-purpose control mechanisms that modulate the operation of various cognitive subprocesses and thereby regulate the dynamics of human cognition" [53]. Inhibitory control is one of the core elements of executive function, along with working memory and cognitive flexibility. It involves "being able to control one's attention, behavior, thoughts, and/or emotions to override a strong internal predisposition or external lure, and instead do what's more appropriate or needed" [16].

As mentioned earlier, the initial misconceptions would exist in the long-term memory and compete with the newly acquired scientific conceptions (see a comprehensive review in Ref. [54]). When the competition occurs, inhibitory control can help students avoid making interference based on the misconceptions [46,55,56]. For example, Babai *et al.* found that participants required more reaction time to determine the correctness of scientific stimuli incongruent with their initial misconceptions compared to those congruent with their initial misconceptions [55,56]. The reaction time differences could be attributed to the incongruity between the scientific definition and the initial misconception. More importantly, the results revealed that correctly judging statements incongruent with the initial misconceptions were more demanding than the congruent ones, which may reflect the involvement of inhibitory control in overcoming the interference of prior misconceptions [55–57].

Recent studies that used the NP paradigm provided more direct evidence to support the role of inhibiting initial misconceptions in conceptual problem solving. For example, Babai *et al.* utilized the NP paradigm to design a task of comparing perimeters of geometrical shapes [11]. According to the NP paradigm, a task should consist of pairs of priming and probing stimuli [58]. These stimuli could be congruent or incongruent with the misconception that "the shape with a larger area has a larger perimeter (larger area–larger perimeter)" (see examples in Fig. 2) [11]. Compared with the congruent stimuli, participants inhibited the misconception when they answered the incongruent stimuli correctly. The inhibition resulted in a longer reaction time (a typical NP effect) for the congruent stimuli (probes) that were preceded by the incongruent

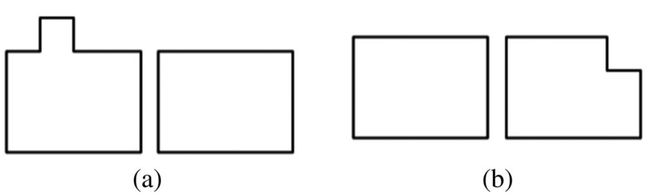


FIG. 2. Examples of the stimuli congruent and incongruent with the misconception "the shape with a larger area has a larger perimeter (larger area–larger perimeter)" in Babai *et al.'s* study [11]. (a) Congruent: the correct response is in line with the misconception "larger area—larger perimeter" and (b) Incongruent: the correct response runs counter to the misconception "larger area—larger perimeter".

stimuli (primes) than that was preceded by the congruent stimuli (primes).

Potvin *et al.* further investigated the association between the initial misconception's interference intensity and NP effects [57]. The study designed three types of priming stimuli to trigger increasingly higher interference intensity caused by the initial misconception that "heavy objects sink more than lighter ones." The task included an intuitive stimulus (a big lead ball and a small wood ball), a neutral stimulus (a lead ball and a wood ball of the same size), and a counterintuitive stimulus (a small lead ball and a big wood ball). The reaction times for probes preceded by different primes increased from intuitive to neutral to counterintuitive primes, which suggested that the increase in interference intensity elicited stronger NP effects [57].

Studies with functional magnetic resonance imaging (fMRI) and event-related potential (ERP) techniques further indicated the neural mechanism underlying the inhibition control's involvement in overcoming the prior misconceptions. Masson *et al.* found that undergraduate physics students activated the brain areas (e.g., the anterior cingulate cortex) that are classically associated with inhibitory control in solving electric circuit problems [13]. Brault Foisy *et al.* revealed that, in overcoming a common physics misconception in mechanics, the scientific (conflicting with the misconception but congruent with the scientific knowledge) and nonscientific stimuli (congruent with the misconception but conflicting with the scientific knowledge) yielded different degrees of activation in the brain regions associated with inhibition control (e.g., the right ventrolateral prefrontal cortex) [5]. Zhu *et al.* further showed that the nonscientific stimuli have more requirements for inhibitory control at the later stage of processing, as evident by larger late positive potential (LPP, an indicator of conflict resolution and response selection based on scientific knowledge) amplitudes compared to scientific stimuli [15].

In summary, previous studies have revealed the function of inhibitory control in solving physics conceptual problems, in which an intuitive conception interferes with the scientific knowledge of electricity [13,15] and mechanics [5]. However, to our knowledge, the inhibitory control mechanism in the domain of kinematics remains poorly understood. For example, the PVI misconception [24] competes with the scientific knowledge of velocity as a ratio of displacement and time elapsed. However, correctly calculating the velocity of an object involves a process of ratio reasoning [27], which is more complicated and complex than the activation of memorized scientific knowledge or even scientific facts studied in previous studies [5,13,15]. Therefore, it is necessary to first investigate whether inhibitory control is involved in inhibiting the common initial misconceptions in kinematics when students correctly respond to the conceptual problems using more complex scientific knowledge rather than memorized facts.

Moreover, recent ERP and fMRI studies revealed the difference in inhibitory control requirement between scientific and nonscientific stimuli [5,15]. According to Potvin's prevalence model, explicit scientific stimuli may increase the priority of scientific conception, which may require less inhibition of the initial misconception [9]. The nonscientific stimuli, in turn, may enhance the misconception by explicitly activating and/or applying it, which may later require more inhibition of the initial misconception in order to arrive at the scientific answer. Hence, it is necessary to further investigate the different degrees of inhibitory control required by stimuli explicitly or implicitly eliciting the initial misconception of kinematics.

C. The current study

The PVI misconception (i.e., two objects are considered to have the same speed at the instant of passing each other) is one of the most documented and prevalent initial misconceptions in kinematics [24,27]. Trowbridge and McDermot developed a classical task that requires students to compare the simultaneous motion of two identical balls when one ball travels with a constant velocity while the other ball travels in the same direction under constant acceleration. The task had profound enlightenment for the subsequent investigations of students' conceptual understanding of kinematics, e.g., the FCI developed by Hestenes *et al.* and the kinematics concept test (KCT) recently developed by Lichtenberger *et al.* [24,25].

Previous studies have shown that even in college physics students, the PVI initial misconception coexists with the scientific conception [24–27]. However, it remains unclear whether college physics students could inhibit the intuitive conception of comparing objects' velocities. Furthermore, the initial misconception would be cued in an explicit or implicit way. Whether there exist different degrees of inhibitory control when students correctly answer the questions, either explicitly or implicitly cueing the initial misconception, also needs to be explored. Investigating the two issues will provide useful insights into understanding the process of conceptual learning in physics. Thus, the present study seeks to answer the following two research questions:

RQ1: Is inhibitory control involved in overcoming the PVI initial misconception in kinematics?

RQ2: If so, to what extent does the degree of inhibitory control differ when students correctly answer questions designed with stimuli cuing the initial misconception in an explicit and an implicit way, respectively?

To answer these research questions, we adopted the NP paradigm to detect the involvement of inhibitory control in overcoming the PVI initial misconception among college physics majors. The NP paradigm is an effective paradigm that has been used in many studies to detect related issues [11,12]. The primary logic of the paradigm is that if a misconception is inhibited in a preceding process, its reactivation during the present process will be more difficult than when it is not inhibited in the preceding process. The former case often leads to a slower or less accurate response (referred to as an NP effect). By comparing the effects of NP under different experimental conditions, we could infer how the inhibitory control may be involved in different cognitive processes.

According to the paradigm's logic and our research questions, we designed four types of items, i.e., the neutral, incongruent-explicit (incongruent-E), incongruent-implicit (incongruent-I), and congruent items (shown in Fig. 3). The prototype for our items came from Item 19 in Hestenes *et al.*'s 1995 version of the FCI. It has been used as a prototypical item for probing the PVI misconception effectively [57]. We designed the items based on it and Items 1 and 25 in the KCT [24,25]. Specifically, each item

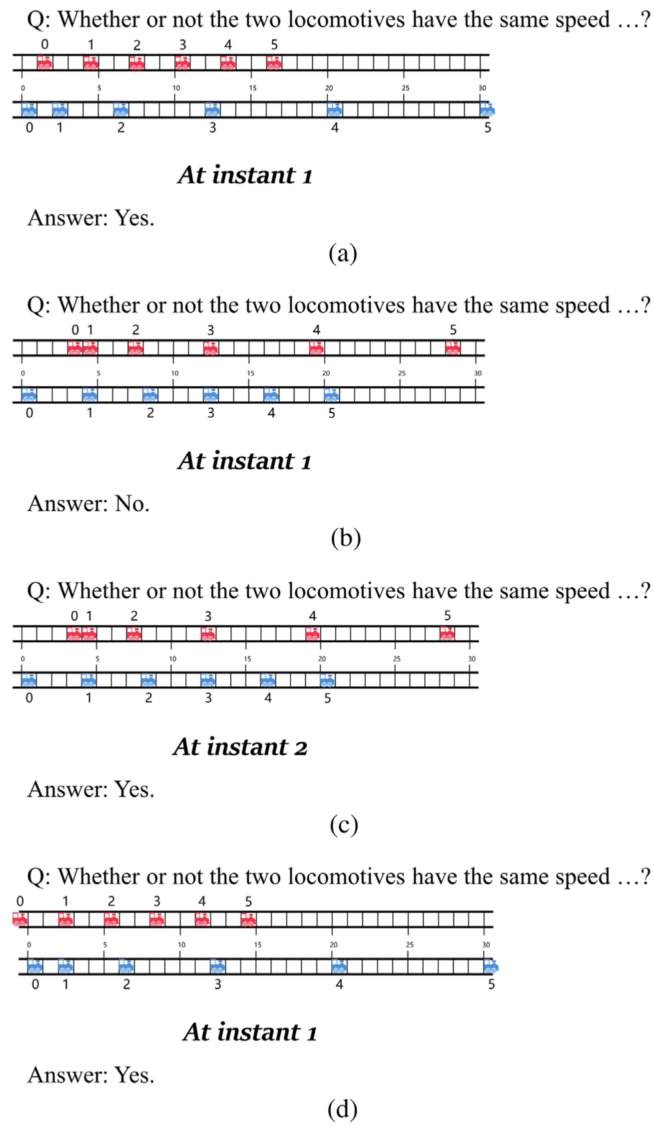


FIG. 3. Examples of the neutral (a), incongruent-E (b), incongruent-I (c), and congruent (d) items used in the negative priming paradigm.

consisted of two locomotives moving in the same direction on a horizontal track, from left to right. One of them travels with a constant velocity, while the other one travels under a constant acceleration in the direction of its velocity (speeding up) or in the opposite direction (slowing down). A diagram depicting a strobe-light photograph was presented to show where the two locomotives would appear in successive positions with 1.0-s intervals.

The participants need to judge whether the two locomotives have the same speed at a specific instant (e.g., instant 1 or 2 shown in the diagram). The key to making a correct judgment is based on the scientific idea that the average velocity of an object undergoing uniform acceleration is the same as the instantaneous velocity at the midpoint of the time interval. The above knowledge has been emphasized repeatedly in high school physics instruction in China. Through repeated training, the vast majority of students in China have long understood and been able to apply the above knowledge. In the Appendix, a more detailed explanation of both the overall judging process and the involved scientific knowledge is presented.

We designed the congruent, incongruent, and neutral items based on whether the scientifically correct answer to a question is consistent, inconsistent, or unrelated to the PVI initial misconception predicted. As shown in Fig. 3, the neutral items do not involve the PVI initial misconception because there is no passing point between the two objects (i.e., they have the same speed at an instant with different positions). In such cases, participants would not automatically activate the misconception when solving the problem. The congruent items refer to the ones for which the correct answer is consistent with what the misconception implies (i.e., the two objects have the same speed at the same position). The misconception is likely activated when students see this type of item. Since the scientific concept and the misconception would predict the same correct answer, students do not need to inhibit the misconception in order to correctly answer the questions.

The incongruent items' correct answers are inconsistent with what the misconception predicts (i.e., the two objects have different speeds at the same position). In these cases, since the two objects have the same position in some instants of concern, participants would automatically activate their misconceptions based on these features. Therefore, participants need to inhibit the PVI misconception to answer these questions correctly. Considering RQ2, we further divided the incongruent items into incongruent-E and incongruent-I items. These two types of projects are similar in having the same positions at instants 1 and 3 as depicted by the strobe-light photograph, which may implicitly cue the PVI misconception. The difference between the two types of items is the question statement to be judged. Specifically, the incongruent-I item asks for the speed at instant 2, where the scientific answer does not pose a direct link to the students' misconception. In comparison, the incongruent-E item asks for the speed at instant 1, which may cue students into explicit activation and application of the misconception. Accordingly, it can be argued that the incongruent-I item cues the PVI misconception only implicitly through the strobe-light photograph, whereas the incongruent-E item cues the misconception explicitly through the strobe-light photograph along with the statement to be judged. Based on this, it is further assumed that the misconception inhibition for incongruent-E items would be higher than that for incongruent-I items.

To answer RQ1, we first grouped these items into pairs of prime-and-probe items in test and control conditions. The probes in these conditions are always congruent items. In the test condition, the congruent probe item is preceded by an incongruent prime item (incongruent-congruent pairs). In the control condition, the congruent probe item is preceded by a neutral prime item (neutral-congruent pairs). The PVI initial misconception is likely activated when students are presented with objects having the same position at a particular instant (as suggested by the intuitive rule *Same A* (position)-*Same B* (velocity) [31]). If so, they need to inhibit the misconception in order to correctly answer the incongruent questions (as shown in Fig. 4). In that case, it is expected to observe a longer reaction time and/or lower accuracy on the incongruent prime items than on the neutral prime ones [55,56] (Hypothesis 1a). In addition, based on the rationale of the NP paradigm, if the PVI misconception is inhibited in processing a prior incongruent prime item, it would be difficult to be reactivated in processing a later congruent probe item [59]. Accordingly, we would observe the typical NP effect indicated by longer reaction time and/or lower accuracy in the test conditions (incongruent-E-congruent and incongruent-I-congruent pairs) than in the control condition (neutral-congruent pairs) (Hypothesis 1b).

To answer RQ2, we further compared the NP effects between the incongruent-E-congruent and incongruent-I-congruent pairs in the test conditions. The incongruent-E and incongruent-I primes are assumed to activate the PVI initial misconception explicitly and implicitly, respectively. Based on previous findings [5,15], the PVI misconception is hypothesized to be inhibited to a greater extent in the incongruent-E questions than in the incongruent-I ones (as shown in Fig. 4), which would result in a larger NP effect in the incongruent-E-congruent pairs than in the incongruent-I-congruent pairs. Accordingly, we expected to observe that the reaction time and/or accuracy difference between the neutral-congruent and incongruent-E-congruent pairs is larger than that between the neutral-congruent and incongruent-I-congruent pairs (Hypothesis 2).

The series of hypotheses tested in the current study were summarized as follows:

H1a. College physics majors will spend more reaction time and/or perform less correctly in answering the

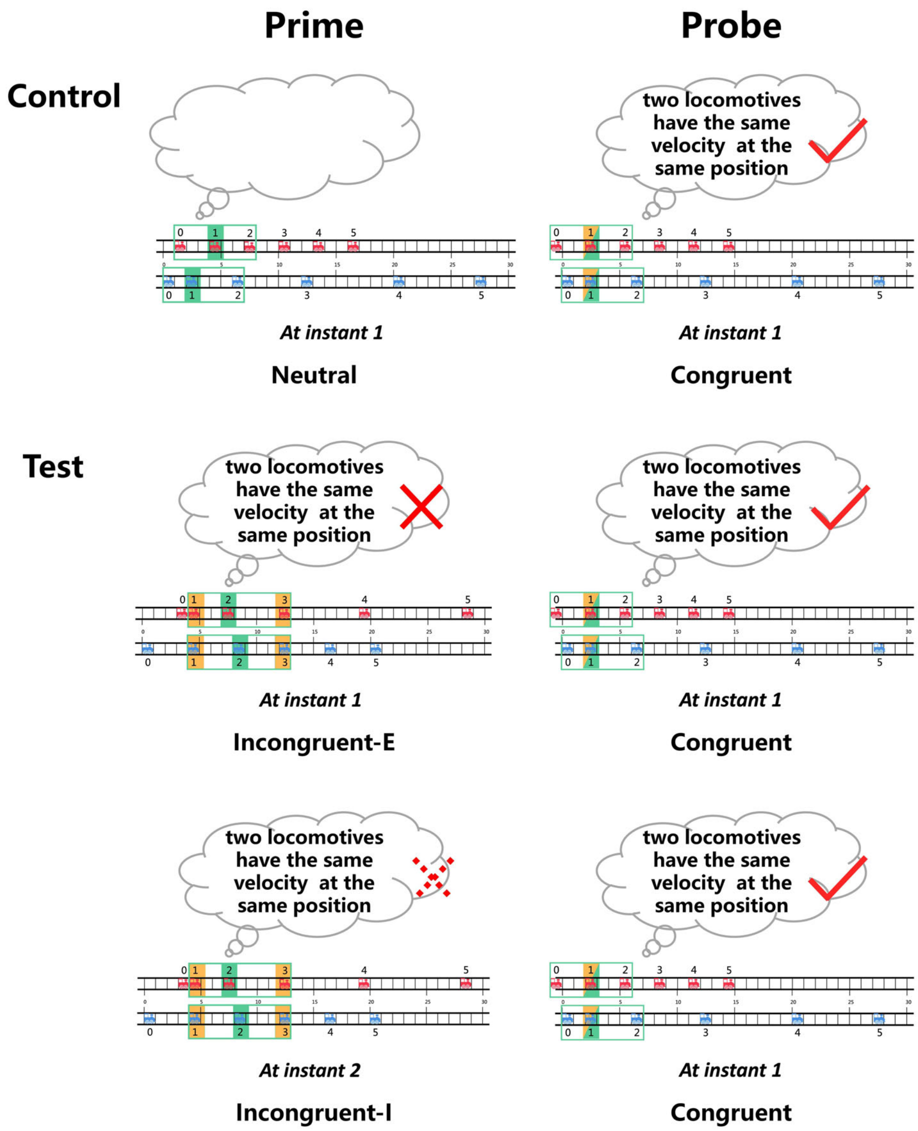


FIG. 4. Examples of the prime-probe pairs in the control and test conditions. In the neutral item, the empty speech bubble indicated that the initial misconception is not represented because the two locomotives did not have a passing point. In the incongruent items, the crossed speech bubble indicated that the misconception may be activated by the passing points (instant 1 or 3), and it should be inhibited to respond correctly. Moreover, it is assumed that the misconception is inhibited to a lesser extent in the incongruent-I items than in incongruent-E items (depicted by a cross in a dotted line and a solid line, respectively). Finally, in the congruent item, the tick indicates that the initial misconception is automatically triggered but it can also lead to the correct answer. Note that the boxes were only used to make it easier for the reader to distinguish the instants in the same position (depicted by yellow) from the instants having the same velocity (depicted by green).

incongruent-E and incongruent-I prime items than the neutral prime items.

H1b. College physics majors will spend more reaction time and/or perform less accurately on congruent probe items that are preceded by the incongruent-E and incongruent-I prime items than on congruent probe items that are preceded by the neutral prime items (i.e., the typical NP effects).

H2. The NP effect elicited by incongruent-E-congruent pairs will be larger than that elicited by incongruent-I-congruent pairs.

III. METHODOLOGY

A. Materials

We designed 24 neutral, 12 congruent, 24 incongruent-E, and 24 incongruent-I items based on Item 19 in the 1995 version of the FCI and Items 1 and 25 in the KCT [24,25] (as shown in Fig. 3). Before the experiment, two of our authors and six physics teachers evaluated the items' validity. They confirmed that the items were effective for assessing college physics majors' understanding of kinematics, especially velocity. We used these items to construct six

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

Condition		Prime item	Probe item	N
Control	1	Neutral	Congruent	12
Test	2	Incongruent-I	Congruent	12
	3	Incongruent-E	Congruent	12
Filler	4	Neutral	Incongruent-E	12
	5	Incongruent-I	Incongruent-E	12
	6	Incongruent-E	Incongruent-E	12

experimental (control, test, and filler) conditions of prime-probe pairs, with 12 pairs for each condition (see Table I). In order to hide the experiment's main purpose and balance the "correct" and "incorrect" responses of probe items (avoiding participants' correct response bias), we added different prime-probe pairs as the filler condition, i.e., neutral, incongruent-E, and incongruent-I items as primes and incongruent-E items as probes. Therefore, each participant needs to complete 72 prime-probe pairs in total.

B. Participants

Thirty participants took part in the study (15 men and 15 women; mean age = 19.7 years). These participants were undergraduates majoring in physics at South China Normal University in Guangdong, China. All participants took physics as a compulsory subject during their high school and college education. To ensure that the participants had a scientific understanding of velocity, after completing the tasks, they were asked to define velocity and explain how they compare velocity. All participants correctly defined velocity and proficiently understood the scientific knowledge involved in performing the velocity comparison tasks, which further confirmed the items' validity. All participants are right handed, native Chinese speakers with normal (or corrected) vision without color blindness.

An *a priori* power analysis was conducted using G*Power 3.1.9.2 to determine the minimum sample size required to test the proposed hypotheses. It was revealed that a minimum of 28 participants would be needed to detect a medium effect size of 0.25 in a three-level within-groups design (types of priming items: neutral, incongruent-I, and incongruent-E) analysis of variance (ANOVA) with 80% power at a significance criterion of $\alpha = 0.05$. Thus, the obtained sample size of 30 is adequate to test the study hypotheses.

C. Procedure

The experimental procedure was adapted from a previous NP study on the involvement of inhibitory control in overcoming the "bigger objects sink more" misconception [12]. The rationale for the NP paradigm adaptation of our velocity comparison task has been presented earlier in Fig. 4. The designed items were arranged in different experimental conditions. In the control condition, a neutral item (in which the PVI misconception neither facilitates nor hinders the velocity comparison) was presented as the prime, and a congruent item (in which the PVI initial misconception is likely activated, which also leads to the correct answer) was presented as the probe. In the test condition, an incongruent-E or incongruent-I item (in which the PVI misconception must be inhibited to a certain extent to reach a correct answer) was displayed as the prime, followed by a congruent item as the probe. In the filler condition, a neutral, incongruent-E, or incongruent-I item served as the prime, and the incongruent-E item served as the probe.

At the beginning of the experiment, each participant was presented with instruction slides and 12 training trials, 4 for each experimental condition, different from the ones presented in the experiment session. After the training trials, all of the participants reported they had become familiar with the tasks' requirements, the visual aspects of stimuli, and the procedure of experiments.

In the formal experiment, as shown in Fig. 5, each trial started with the presentation of a fixation cross (500 ms), followed by a strobe light diagram for two locomotives along with a statement comparing the speeds of the locomotives (the prime). The participants needed to evaluate whether the statement was correct or not as fast and as accurately as possible, by pressing the "F" or "J" key on a standard keyboard with their left or right hand's index fingers. The pressing keys and their corresponding figures were contour balanced among participants. As soon as participants provided an answer, a fixation cross was displayed (500 ms), followed by another strobe light diagram for two locomotives along with a statement comparing the speeds of the locomotives (the probe). The participants also needed to evaluate the statement's correctness by pressing the corresponding buttons. Once the participants responded to the probe, a fixation cross was displayed for 500 ms, followed by a visual mask of white noise for 2000 ms. These trials, composed of pairs of prime-probe items in six conditions, were presented in a random order.

The experiment was presented on a laptop computer with a 1920×1080 pixels resolution and a refresh rate of 60 Hz using E-prime 3.0 software (Psychology Software Tools, Inc., Pittsburgh, PA, USA). For each presented item, the software recorded the accuracy (ACC) of classification (correct or incorrect) and the participant's reaction time (RT). RT has been demonstrated as an effective independent variable in plenty of psychological behavioral studies. Previous studies [12,60] on the involvement of inhibitory control using the NP paradigm also used RT and ACC as indicators. Moreover, in these studies, RT was found to be a more reliable indicator of inhibitory control than ACC [57,60]. Therefore, we considered the RT and ACC in our study simultaneously.

D. Data analysis

The filler trials were used to hide the experiment's main purpose and balance the correct and incorrect responses to

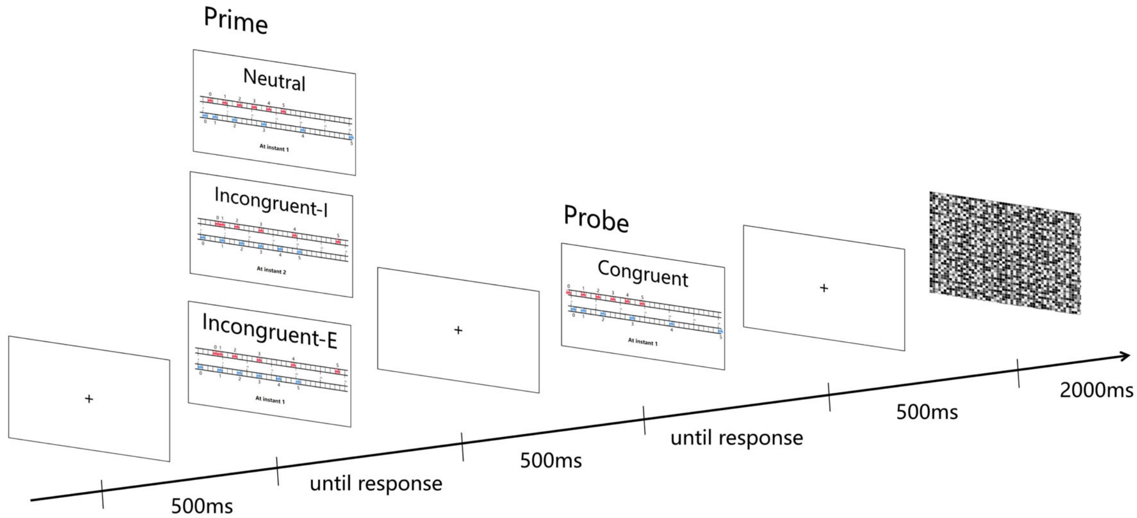


FIG. 5. The experimental procedure for the control (neutral as prime-congruent as probe) and test conditions (incongruent-E or incongruent-I as prime-congruent as probe).

probe items. We excluded the data from these filler trials and only analyzed the data from the test and control trials. The ACCs and RTs of correctly performed items were calculated separately for the primes and probes. It's noted that we only calculated the ACCs and RTs of the probes if the correct answers to their primes were given. Logistic and linear mixed-effects models were conducted on the prime and probe's ACC and RT data, respectively, running with the lme4 package [61] and the lmerTest package [62] in the statistical software R. The mixed-effects models are preferable to an ANOVA because they allow the random effects of participants and items to be considered simultaneously, making the data modeling more appropriate and the results more generalizable to other participants and items. The three types of prime-probe pairs (congruent items preceded by neutral, incongruent-E, and incongruent-I primes) were entered into the model as fixed effects with dummy coding, identifying the neutral condition as the reference group. For the random effects, we tried to have intercepts for participants and items, as well as by-participant and by-item random slopes for the effect of types of items. However, in the final fitted models, only the by-participant intercept was suggested to be kept, and other factors were consequently excluded as they did not contribute to the variance in the models based on the principal component analyses (PCA) [63].

To test hypothesis 2, we calculated the NP effects (i.e., the RT difference between congruent probes preceded by an incongruent item and those preceded by a neutral item) for the incongruent-E-congruent and incongruent-I-congruent pairs, respectively. Then, a linear mixed-effects model was also conducted on the NP effects data. This time, the two types of prime-probe pairs were entered into the model as fixed effects with contrast coding (i.e., incongruent-I $= -0.5$, incongruent-E $= 0.5$), which could get the results of main effects analogous to those obtained from ANOVA. For the random effects, a similar final fitted model suggested only keeping the by-participant intercept.

IV. RESULTS

A. Performances on different types of primes

Table II presents the mean ACCs and RTs for the neutral, incongruent-I, and incongruent-E priming items. First, a logistic mixed-effects model was fitted to the ACC data on the three types of prime. The results revealed a marginally significant main effect of priming types [$F(2, 1048) = 2.89$, $p = 0.056$], with ACC in the incongruent-E primes being significantly lower than the neutral primes ($\beta = -0.75$, $\mathrm{SE} = 0.33$, $Z = -2.29$, $p < 0.05$, incongruent-E < neutral). However, there is no significant difference between the incongruent-I (94.8%) and neutral primes (96.2%, $\beta = -0.25$, $\mathrm{SE} = 0.35$, $Z = -0.71$, $p = 0.497$) or incongruent-E primes (92.5%, $\beta = 0.50$, $\mathrm{SE} = 0.31$, $Z = 1.64$, $p = 0.102$).

A linear mixed-effects model was fitted to the RTs data on the three types of primes, with the same fixed structure and random effects as in the model for ACC. The results revealed a significant main effect of priming types [$F(2, 1048) = 37.77$, $p < 0.001$], with RT in the incongruent-E primes (7275 ms) being significantly longer than the neutral (4949 ms, $\beta = 2536$, $\mathrm{SE} = 321$, $t = 7.90$,

TABLE II. Mean accuracies (ACCs) and reaction times (RTs) for the neutral, incongruent-I, and incongruent-E priming items (standard deviations in parentheses).

Stimuli type	ACC	RT/ms
Neutral prime	0.962 (0.05)	4949 (1813)
Incongruent-I prime	0.948 (0.08)	5358 (2155)
Incongruent-E prime	0.925 (0.10)	7275 (3263)

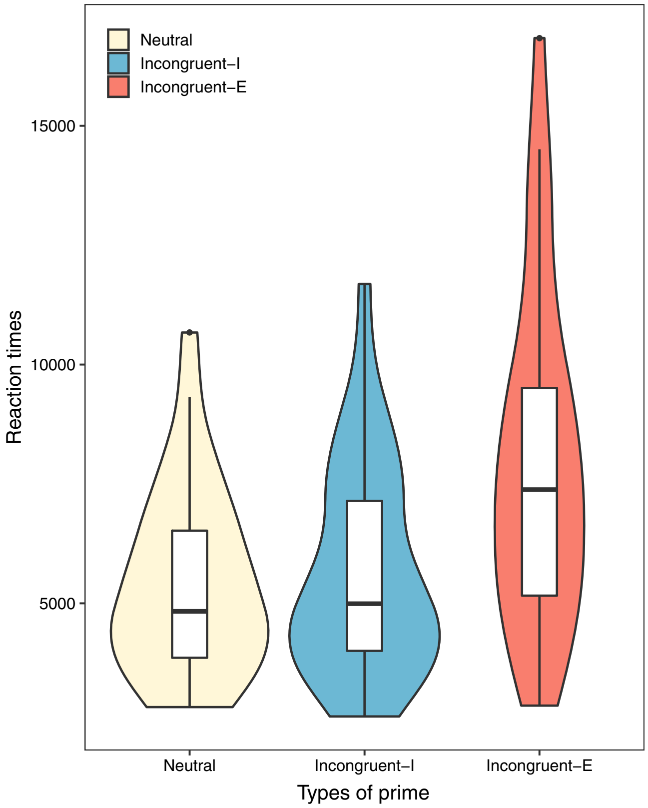


FIG. 6. Reaction times (RTs) for the neutral, incongruent-I, and incongruent-E priming items.

$p < 0.001$, incongruent-E > neutral) and incongruent-I primes (5358 ms, $\beta = 2276$, SE $= 321$, $t = 7.09$, $p < 0.001$, incongruent-E > incongruent-I; see Fig. 6). However, there is no significant difference between the incongruent-I and neutral primes ($\beta = 260$, SE $= 321$, $t = 0.81$, $p = 0.419$).

B. Performances on the congruent probes preceded by different types of primes

Table III presents the mean ACCs and RTs for the congruent probe items that were preceded by the neutral, incongruent-I, and incongruent-E prime items. First, a logistic mixed-effects model was fitted to the ACC data on the congruent probe items preceded by different types of primes. The results revealed a significant main effect of priming types [$F(2, 1048) = 3.83$, $p = 0.022$], with ACC

TABLE III. The mean accuracies (ACCs) and reaction times (RTs) for the congruent probe items preceded by the neutral, incongruent-I, and incongruent-E prime items (standard deviations in parentheses).

Probe preceded by	ACC	RT/ms
Neutral prime	0.990 (0.03)	4021 (1649)
Incongruent-I prime	0.973 (0.05)	4685 (2485)
Incongruent-E prime	0.954 (0.09)	5994 (2777)

in the congruent probes preceded by incongruent-E primes being significantly lower than that preceded by neutral primes ($\beta = -1.78$, SE $= 0.65$, $Z = -2.77$, $p < 0.01$, incongruent-E < neutral). However, there is no significant difference between the congruent probe items preceded by incongruent-I primes (97.3%) and those preceded by neutral primes (99.0%) ($\beta = -1.03$, SE $= 0.68$, $Z = -1.50$, $p = 0.133$) or those preceded by incongruent-E primes (95.4%) ($\beta = 0.75$, SE $= 0.45$, $Z = 1.65$, $p = 0.099$).

Similarly, a linear mixed-effects model was fitted to the RTs data on the congruent probe items preceded by the three types of primes, with the same fixed structure and random effects as in the generalized mixed-effects model for ACCs. The results also revealed a significant main effect of priming types [$F(2, 1048) = 40.475$, $p < 0.001$], with RT in the congruent probe items preceded by incongruent-E primes (5994 ms) being significantly longer than that by neutral primes (4021 ms, $\beta = 2054$, SE $= 235$, $t = 8.76$, $p < 0.001$, incongruent-E > neutral) and by incongruent-I primes (1471 ms, $\beta = 2276$, SE $= 321$, $t = 6.25$, $p < 0.001$, incongruent-E > incongruent-I) (see Fig. 7). Meanwhile, RT was also significantly slower in the congruent probe items preceded by incongruent-I primes than those preceded by neutral primes ($\beta = 582$, SE $= 233$, $t = 2.50$, $p = 0.03$, incongruent-I > neutral).

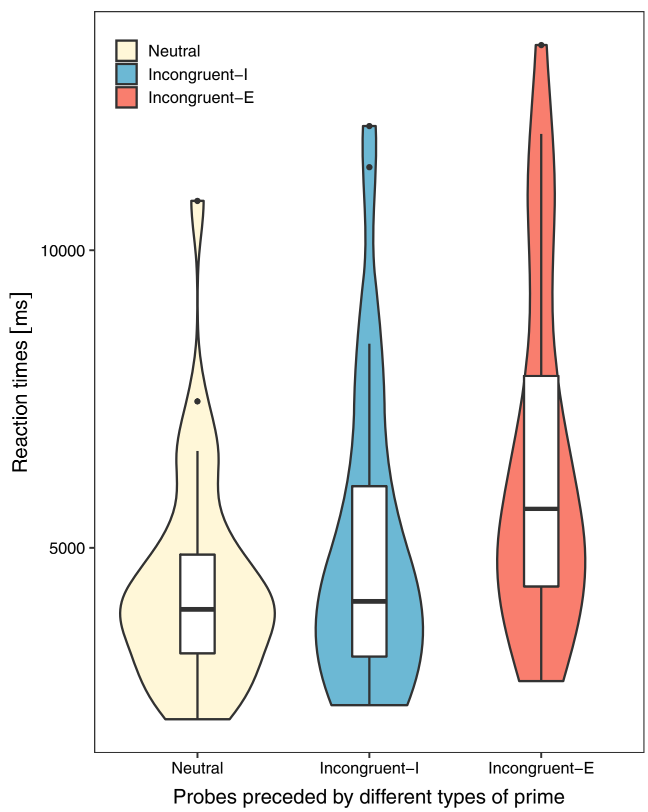


FIG. 7. Reaction times (RTs) for the congruent items (probe) preceded by neutral, incongruent-I, and incongruent-E items.

Finally, a similar linear mixed-effects model was fitted to the NP effects on the congruent probing items preceded by two types of incongruent primes. Results of the model showed that the main effect of priming types was significant ($\beta = 1351.10$, $\mathrm{SE} = 337.64$, $t = 4.00$, $p < 0.001$; congruent probes preceded by incongruent-E primes > congruent probes preceded by incongruent-I primes).

V. DISCUSSION

The study aimed to determine (i) whether inhibitory control of the PVI initial misconception is needed for college physics majors to compare objects' velocities and (ii) to what extent the degree of inhibitory control differs when correctly answering incongruent items activating the initial misconception in explicit and implicit ways, respectively. If they do, students are expected to perform worse in the incongruent primes than the neutral primes and also in the congruent probes preceded by the incongruent primes than by neutral primes (a typical NP effect). Moreover, a greater degree of NP effect is expected in the congruent probes preceded by the incongruent-E primes than by the incongruent-I primes.

A. Inhibitory control is needed to overcome the PVI misconception in kinematics

The results regarding participants' performance on the incongruent priming items and congruent probing items preceded by incongruent priming items provided evidence for our first hypothesis. Following previous findings, analysis of priming items reproduced the classical interference effect caused by the PVI initial misconception (i.e., the difference in performance between the neutral and incongruent priming items) [11,12,57]. Interestingly, this interference effect was only significant for incongruent-E items that explicitly activated the PVI misconception. These results suggested that the statement, together with the strobe light diagram for two locomotives with passing points, which were depicted by incongruent-E items, triggered a conflict between the misconception and the scientific knowledge. As the strobe light diagram in incongruent-I items only implicitly cues the initial misconception, the passing points of the two locomotives shown in the diagram are expected to not produce a substantial level of conflict compared to the neutral items. However, the results did not preclude the necessity of inhibiting the initial misconception. It is also possible that the scientific statement in incongruent-I items caused students to automate their scientific response pattern as scaffolding, reducing their conscious perception of the misconception [5]. The unconscious perception of the misconception may still be activated, and therefore, the inhibition of the misconception was also needed.

Another observation from the probes strongly supported this claim. Indeed, typical NP effects were found for the congruent probe items preceded by incongruent-E and incongruent-I prime items, i.e., longer RTs were observed in response to the congruent probe items preceded by incongruent-E or incongruent-I prime items than those preceded by neutral prime items. Although the difference between the ACCs for congruent probe items preceded by incongruent-I prime items and those preceded by neutral prime items did not reach the statistically significant level ($p = 0.099$), the NP effects were in the same direction, as shown in Table II. Taken together, inhibition would be required for college physics majors to overcome the PVI misconception in comparing objects' velocity for the two types of incongruent items.

Our results also challenged the claim that "difficulty of the primes… is unlikely to be at the root of the NP effects reported." [12]. The complexity of misconception and the scientific conception involved in our task were different from simply memorized scientific knowledge or even scientific facts investigated by previous studies in the domain of "mechanics" and "floating and sinking" [5,12,13,57]. For example, in the previous NP studies on the inhibition of misconceptions in floating and sinking, participants only needed an average of less than 1000 ms RTs to correctly answer the question, and inhibition of a misconception was usually associated with longer RTs with differences less than 100 ms (NP effects) [12,57]. The current study found longer RTs (an average of 4021–7275 ms) and larger NP effects (664 and 1973 ms), which suggested that the activation of more complex scientific knowledge and the suppression of initial misconceptions require a greater degree of inhibitory control. Accordingly, our study also provides preliminary evidence that the degree of required inhibitory control may be associated with the complexity of scientific knowledge and/or misconceptions involved in the tasks.

B. The requirement of inhibitory control is different for incongruent-E and incongruent-I items

We observed that physics majors' evaluation of incongruent-I and incongruent-E prime items involved different degrees of inhibitory control for overcoming the PVI initial misconception. They needed significantly longer RTs for congruent probing items preceded by the incongruent-E and incongruent-I primes than by the neutral primes. Moreover, the difference RT in between the incongruent-E and neutral primes was bigger than the difference between the incongruent-I and neutral primes (NP effect differences).

The results first suggested that the incongruent-E items (where the misconception was explicitly activated) demanded a greater degree of inhibitory control than the incongruent-I items (where the misconception was implicitly activated), which is in-line with previous findings [5,15]. Brault Foisy claimed that inhibitory control is required for both nonscientific and scientific stimuli, but it is more strongly associated with the former than the latter [5]. Zhu *et al.'s* ERP study further revealed that these two stimuli involved similar patterns of inhibitory control in the earlier time course of processing. However, in the later processing, the nonscientific stimuli required a larger degree of inhibitory control than scientific stimuli [15]. In the present study, the students were found to have to overcome their misconceptions to respond correctly to both the incongruent-E and incongruent-I priming items. This cognitive processing based on a misconception would precede the processing based on scientific knowledge [15]. Accordingly, a plausible explanation for the difference between the two types of items is that the statement consistent with scientific knowledge in the incongruent-I items may serve as an external scaffold to help students speed up or automatically override the information processing based on the scientific knowledge, which finally inhibits the initial misconception invoked earlier.

Furthermore, our NP results also reflected that the retention of inhibiting an initial misconception was different between the time courses for processing the incongruent-E and incongruent-I priming items. In our study, the NP effect elicited by the incongruent-I prime items was smaller than that elicited by incongruent-E prime items. It is possible that the statements in the incongruent-E items explicitly activate the misconception and enhance its involvement in problem solving, which required a larger degree of inhibitory control than the incongruent-I items. Another plausible explanation is that the statement consistent with scientific knowledge provided by the incongruent-I items may contribute to conflict resolution and response selection based on the scientific knowledge [15]. The cognitive process for inhibiting the misconception may have been reduced by the statement consistent with scientific knowledge because the scientific knowledge was highlighted and hence prevailed over the misconception.

C. Models of conceptual change and effective physics instruction

Our results provided substantial evidence for theoretical debate about what happens to the initial misconception after a conceptual change. In our study, the students performed worse on the incongruent items than the neutral items, which indicated that the misconception would not disappear or be radically transformed after a conceptual change. The results are hardly compatible with the models suggesting that the process of conceptual change is fundamentally or radically reconstructed and that the initial misconceptions are no longer accessible after a conceptual change [1,19,34,35]. In contrast, the results are in favor of models of conceptual change advocating the coexistence of alternative conceptions, and the initial misconceptions were surpassed by rather than entirely supplanted by scientific conceptions [9,13–15,45,64–67].

The results regarding the difference in inhibitory control required by the incongruent-E and incongruent-I items are also consistent with the prevalence model proposed by Potvin [9]. Potvin's prevalence model assumed that increasing the prevalence of the scientific conception required less inhibition of the initial misconception. Accordingly, while inhibitory control is needed for dealing with the interference caused by the initial misconception, it becomes less needed in the incongruent-I items as the scientific conception becomes more prevalent after being enhanced by the presented statement consistent with scientific knowledge. On the other hand, in the incongruent-E items, the misconception becomes more prevalent after being enhanced by the presented statement explicitly activating it, which requires a larger degree of inhibition of the initial misconception.

The current study's findings also have some implications for the development of effective instructions to improve students' conceptual understanding and problem-solving abilities. While it has been widely agreed in the physics education community that students' initial misconceptions should be carefully considered, a consensus on the timing for exposing initial misconceptions and achieving the desired scientific conceptions has yet to be achieved. The classical models always suggested a cognitive conflict type of instruction, in which initial misconceptions were exposed as the first step toward successful conceptual change [19,36,47,50]. However, Potvin *et al.'s* recent study found that students who were first subjected to the targeted scientific conceptions benefited more from early cognitive conflict than students who were first subjected to a possible cognitive conflict [49]. That is, making the desired scientific conception available at the very beginning of instruction provided students with "a 'new branch' to grab onto before being invited or incited to let go of the 'old one'" [9] (p. 28). The proposition is consistent with our findings that the incongruent-I items required less inhibitory control than the incongruent-E items.

Finally, as the inhibitory control function was considered a critical role in conceptual learning, it may be valuable to provide students with inhibitory-control-based training or instructions for improving their general ability of inhibitory control. Recent studies have reported that inhibitory-control-based activities have some encouraging positive effects. For example, Letang *et al.* reported that children improved their inhibitory control abilities after 5-week inhibitory-control training conducted by teachers in their classroom [68]. Receiving appropriate inhibitory control training in the learning process can also reduce students' reliance on reasoning based on initial misconceptions [69].

D. Limitations and suggestions for future study

This research has some limitations that need to be considered when interpreting the outcomes. First, the current study was only conducted on 30 physics majors from South China Normal University. While the number of participants was sufficient statistically, our results need to be interpreted carefully as a result of the small number of participants. It should also be cautious when applying our findings to students from other universities and education systems. It would be beneficial to examine if similar results can be replicated with students from different institutions and education settings.

Second, in-line with previous studies, the NP effect, the indicator of inhibitory control, was calculated based on RT in the current study [12,60]. Additional behavioral and neuroscience measurement techniques, such as the eye-tracking method [70,71], ERP [15], and fMRI [5], could be used in future studies to capture an extensive set of measures that can be triangulated to provide a more robust understanding of the possible cognitive processes in solving the PVI problems.

Third, it is unclear whether the requirement of inhibitory control in overcoming the PVI initial misconception in kinematics is different before or after a conceptual change. Future studies under a longitudinal design would be required to investigate the possible change in the requirement of inhibitory control during the developmental course of the student's learning kinematics.

Finally, we only asked participants to compare the velocity of two objects presented in a strobe-light photograph, which was always labeled as a picture or pictorial representation [25,72]. Such a visual representation in nature may be in the favor of those who are visual style learners [73]. However, there is no substantial evidence to support the so-called learning-styles hypothesis (individuals learn best with the material presented in a format that matches their preferences for learning style, e.g., for a "visual learner," emphasizing materials in visual representation) [74,75]. Furthermore, the results cannot be generally extended to other forms of representation of kinematic problems. It would be beneficial to examine if similar results can be replicated using different forms of representation (e.g., a graphical presentation of a position-time graph).

VI. CONCLUSION

The current study investigated whether and how inhibitory control is involved in overcoming a common initial misconception in kinematics using a NP paradigm. The findings revealed that inhibitory control was required for college physics majors to overcome the PVI misconception in comparing objects' velocities with passing points. The explicit activation of the misconception required more inhibitory control. The prevalence of scientific knowledge may promote students' inhibition of the initial misconception.

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APPENDIX: SCIENTIFIC KNOWLEDGE INVOLVED IN CORRECTLY RESPONDING TO THE ITEMS

Each item consisted of two locomotives moving in the same direction on a horizontal track, from left to right. One travels with a constant velocity, whereas the other travels under a constant acceleration in the direction of its velocity (speeding up) or in the opposite direction (slowing down).

The average velocity v_{avg} of a particle is defined as the particle's displacement Δx divided by the time interval Δt during which that displacement occurs

$$v_{\mathrm{avg}} = \frac{\Delta x}{\Delta t}. \tag{A1}$$

For the locomotive with constant velocity, students are expected to understand that its instantaneous velocity at any instant during a time interval is the same as its average velocity over the interval

$$v = v_{\mathrm{avg}} \quad (\text{for constant velocity}). \tag{A2}$$

For the locomotive under constant acceleration, students are expected to understand that it has the same instantaneous velocity in the middle of any time interval as its average velocity over the interval

$$v_{\frac{t}{2}} = v_{\mathrm{avg}} \quad (\text{for constant accelaration}). \tag{A3}$$

The above knowledge has been emphasized repeatedly in high school physics instruction in China. Through repeated training, the vast majority of students in China have long understood and been able to apply the above knowledge. All participants in the current study were asked to define velocity and explain how they compare velocity after completing the tasks. All participants were found to have a proficient understanding of Eqs. (A1)–(A3).

The neutral condition of Fig. 3 was taken as an example for illustrating how to determine a locomotive's instantaneous velocity. The instantaneous speed of a locomotive equals the magnitude of its instantaneous velocity. Let us assume that the interval between any two adjacent instants is 1 s.

For the red locomotive under constant velocity, its instantaneous speed at instant 1 is

$$v_{\text{red}} = v_{\text{avg}} = \frac{\Delta x}{\Delta t} = \frac{6}{2}(\text{space/s}) = 3(\text{space/s}). \quad \text{(A4)}$$

For the blue locomotive under constant acceleration, its instantaneous speed at instant 1 is

$$v_{\text{blue}} = v_{\frac{t}{2}} = v_{\text{avg}} = \frac{\Delta x}{\Delta t} = \frac{6}{2}(\text{space/s}) = 3(\text{space/s}). \quad \text{(A5)}$$

Where Δx in Eqs. (A4) and (A5) represents the displacement from instants 0 and 2.

Hence, the two locomotives have the same speed at instant 1.

The proof of expression (A3) is as follows:

If a particle starts from its initial position x_i and velocity v_i in a straight line with a constant acceleration a, its subsequent instantaneous position and velocity are described by the following kinematic equations:

$$x_f = x_i + v_i t + \frac{1}{2}at^2. \quad \text{(A6)}$$

$$v_f = v_i + at. \quad \text{(A7)}$$

Let us take $t_i = 0$, and t_f to be any later time t, we can find its instantaneous velocity at the midpoint of the time interval of Δt ($\Delta t = t_f - t_i = t$), which is given by

$$v_{\frac{t}{2}} = v_i + a\frac{t}{2}. \quad \text{(A8)}$$

Recalling that Δx in Eq. (A1) represents $x_f - x_i$ and recognizing that $\Delta t = t$, we find that

$$v_{\text{avg}} = \frac{\Delta x}{\Delta t} = \frac{x_f - x_i}{t} = v_i + \frac{1}{2}at. \quad \text{(A9)}$$

Equation (A3) is verified by comparing Eqs. (A8) and (A9). For an object under constant acceleration, its instantaneous velocity at the midpoint of any time interval is the same as the average velocity over the interval.

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