# Inhibitory control and attentional allocation in overcoming position-velocity indiscrimination misconception in position-time graph representation

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Students often hold intuitive misconceptions that coexist with scientifically normative understanding. A growing body of research suggests that inhibitory control plays an important role in resolving such interference by suppressing misconception-based responses. In science learning, however, the same underlying concept is often encountered through multiple external representations, which may repeatedly activate similar misconceptions. It therefore remains unclear whether inhibitory control is also involved when the same concept is expressed in different but closely related representation formats. Extending prior findings on inhibitory control in stroboscopic representation involving the position-velocity indiscrimination (PVI) misconception, the present research examined whether similar demands on inhibitory control arise in position-time graph representations. To address this question, we conducted two studies using a negative priming (NP) paradigm, with eye tracking added in Study 2. Study 1 involved 45 high school students and tested whether inhibitory control was involved in overcoming the PVI misconception in position-time graphs. Study 2 involved 37 physics major undergraduates and further examined how attentional allocation unfolded during this process. In both studies, congruent probes following incongruent primes elicited slower responses than congruent probes following neutral primes, indicating a reliable NP effect. In Study 1, probe accuracy was also lower after incongruent primes. Eye tracking in Study 2 further showed that, during incongruent primes, participants oriented earlier to graph regions in which the two objects occupied the same position, whereas access to the graph region indicating equal velocity, defined by equal slope, was delayed relative to neutral primes. In the probe stage, congruent probes following incongruent primes elicited later entry into, and greater attentional investment on, the graph region that contained the scientifically relevant cue for making the correct velocity judgment. Taken together, these findings suggest that the PVI misconception is activated early, competes for attentional resources, and requires inhibitory control together with attentional reallocation toward scientifically relevant information. More broadly, considered alongside prior evidence from stroboscopic

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representations, the present results provide initial evidence that the inhibitory demands associated with overcoming the PVI misconception may generalize across closely related visual representations of the same kinematic concept. This study advances understanding of the cognitive processes underlying physics learning and offers implications for instruction aimed at mitigating persistent misconceptions.

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## I. INTRODUCTION

In physics education, misconceptions remain a persistent obstacle to meaningful learning because they often coexist with formal scientific understanding rather than disappearing after instruction [1]. Research across science domains has shown that learners may retain intuitive but scientifically incorrect ideas even after acquiring the relevant scientific knowledge, and these ideas can reemerge during problem solving [2–8]. One important example in kinematics is the position-velocity indiscrimination (PVI) misconception, in which learners incorrectly infer that objects at the same position must have the same velocity [3,9,10]. Such a misconception can distort the interpretation of motion and undermine accurate reasoning in kinematics tasks.

Recent cognitive research suggests that overcoming misconceptions is not solely a matter of acquiring the correct concept but also involves executive functions that regulate competition between intuitive and scientific responses [4,8,11]. Among these, inhibitory control has been increasingly recognized as a key mechanism for resolving conceptual conflict. Inhibitory control refers to the capacity to suppress dominant, automatic, or misleading responses in favor of goal-directed ones [12]. In science learning, this process is especially important when learners must override intuitive but incorrect interpretations in order to apply formal scientific understanding. A growing body of evidence indicates that counterintuitive science problems often require additional processing time because learners must suppress misconception-based responses [6,8,11,13]. Consistent with this perspective, recent conceptual change work has emphasized the value of supporting learners in recognizing and resisting contexts in which intuitive reasoning is likely to mislead them [14]. Together, these studies suggest that suppressing intuitive but incorrect ideas may be a necessary condition for successful conceptual change and scientific problem solving.

At the same time, science learning rarely occurs within a single external representation format. In physics instruction, the same underlying concept is routinely expressed through multiple external representations, such as diagrams, graphs, equations, and verbal descriptions [15–18]. These representations can support learning by engaging complementary cognitive processes, enabling learners to construct richer mental models, and facilitating connections across formats [17,19–21]. However, multiple representations may also create repeated opportunities for the same misconception to be activated. For example, students have been shown to apply the same incorrect reasoning across isomorphic physics tasks presented in different forms, suggesting that some misconceptions are sufficiently robust to be triggered across representations [22]. If so, learners may need to repeatedly recruit inhibitory control when encountering the same concept in different formats.

This possibility gives rise to an important unresolved question: does inhibitory control operate consistently across different representational formats of the same concept? Existing research has largely examined inhibitory control within single representation contexts [2,3,23]. Prior work, for example, has shown that inhibitory control is involved in overcoming the PVI misconception in stroboscopic tasks [3]. More recent evidence has also suggested that inhibitory control may be implicated across representational formats. Hong *et al*. reported accuracy (ACC)-based interference effects in both tabular and pictorial formats, but a significant response-time-based Stroop effect only in the pictorial format [24]. This pattern suggests that conceptual or heuristic conflict may emerge and that inhibition is involved across formats, while also leaving open the possibility that substantial differences in task difficulty and cognitive load influence the extent to which inhibitory demands are behaviorally detectable. Thus, it remains unclear whether inhibitory control in conceptual change is tied to specific perceptual forms or reflects a more general representation mechanism. This issue is theoretically important for understanding the cognitive basis of conceptual change and educationally important because some representations may impose lower inhibitory demands than others, thereby leaving more cognitive resources available for learning and reasoning.

Behavioral measures such as reaction time (RT) and accuracy can indicate whether conceptual conflict and inhibitory processing are present, but they provide limited insight into how learners allocate attention while resolving that conflict. Recent research has therefore increasingly used eye tracking to examine the cognitive processing associated with inhibitory control [25–27]. In particular, eye-movement measures can reveal whether learners are initially drawn to misconception-related cues and how attention is subsequently redirected toward scientifically relevant information. Prior work in physics has shown that learners' eye movements often reveal an initial attraction to misconception-related features before attention is

redirected, together with additional attentional investment associated with overcoming misconception-based interference [27]. Such findings suggest that attentional allocation and inhibitory control are closely intertwined during conceptual change, making eye tracking especially useful for clarifying the processes through which misconceptions are activated and overcome.

Accordingly, the present study investigates whether inhibitory control is also involved in overcoming the PVI misconception in position-time ($x-t$) graph representations. To this end, we employed a negative priming (NP) paradigm combined with eye tracking to examine both inhibitory control and attentional allocation during graph-based kinematics reasoning [28,29]. By integrating behavioral and eye-movement evidence, this study aims to clarify whether the suppression of PVI reflects a general representation mechanism across closely related visual representations. In doing so, it contributes to a deeper understanding of the cognitive processes underlying conceptual change and offers implications for the design of instructional strategies intended to mitigate persistent misconceptions.

## II. LITERATURE REVIEW

### A. The coexistence of misconceptions and scientific conceptions

Misconceptions have long been recognized as a major obstacle in physics learning, particularly in mechanics. A large body of research has shown that students often bring to instruction intuitive but scientifically inaccurate ideas about force and motion. For example, learners may believe that no force acts on an object at rest, that heavier objects fall faster than lighter ones [9], or that constant motion requires a continuous applied force, contrary to Newton's first law [30]. Misconceptions also appear in collision contexts, where students may assume that the more massive object exerts the greater force, thereby overlooking Newton's third law [31]. Similar difficulties arise in projectile motion, where students may incorrectly treat horizontal and vertical motion as interdependent [30] or assume that a projectile remains in the air longer because it travels farther horizontally rather than because of its vertical displacement [32]. These examples indicate that misconceptions in physics are not isolated errors but recurrent patterns of reasoning that can systematically interfere with scientific understanding.

Such persistent difficulties have made conceptual change a central topic in science education research. Conceptual change is commonly defined as the process by which learners move from their preinstructional conceptions toward the scientific concepts to be learned [1]. Since the 1970s, researchers have proposed a wide range of models to explain how such change occurs and why it is often difficult to achieve [33]. Indeed, more than 80 distinct models had been identified by 2019 [13], reflecting the diversity of assumptions about the origins of misconceptions and the mechanisms through which they may be transformed [34].

However, the replacement view of conceptual change [35,36] has increasingly been challenged by perspectives that emphasize the complexity and persistence of prior knowledge. Rather than treating misconceptions as stable alternative frameworks that must be eliminated, knowledge-system perspectives argue that learners' reasoning is composed of multiple cognitive resources that are activated differently across contexts [37]. These resources include phenomenological primitives, or p-prims [38], as well as intuitive rules [39], both of which may be productive in some situations but misleading in others. From this perspective, misconceptions do not necessarily reflect the absence of scientific knowledge. Instead, they may arise when familiar intuitive resources are applied inappropriately to scientific problems. For example, the belief that heavier objects fall faster can be interpreted as an overextension of the intuitive rule "More A, More B," in which greater weight is incorrectly associated with greater speed [40]. Importantly, such intuitive rules do not simply disappear after instruction. Rather, they may remain cognitively available and continue to shape reasoning when tasks contain cues that trigger them.

This line of work has led to increasing support for the view that misconceptions and scientific conceptions often coexist rather than replace one another completely [14,41,42]. For example, Solomon [43] proposed that conceptual change involves learning to differentiate between scientific and lifeworld domains, rather than eliminating everyday conceptions altogether. Similarly, Ohlsson [42] argued that multiple conceptions may coexist within the same domain, with one grounded in formal disciplinary knowledge and another drawn from everyday experience to interpret the same phenomenon. In this sense, conceptual change is not simply a matter of removing prior ideas but of learning when and how to activate scientifically appropriate ones. Empirical work likewise suggests that scientific conceptions may become more prevalent after instruction without fully displacing prior misconceptions [7].

This coexistence perspective has important implications for understanding physics learning. If intuitive misconceptions remain available even after learners acquire formal scientific understanding, then successful problem solving depends on more than conceptual acquisition alone. Learners must also manage the competition between scientific and intuitive responses. Conceptual change, therefore, involves not only learning scientific ideas but also regulating the conditions under which competing conceptions are activated and selected. This implication points directly to the importance of cognitive mechanisms that enable learners to suppress misleading intuitive

responses when they conflict with scientifically appropriate reasoning. In the next section, we therefore turn to inhibitory control as a key role that may support such regulation during conceptual change.

### B. Inhibitory control in overcoming misconceptions

If misconceptions and formal scientific understanding can coexist within the same learner, then conceptual change cannot be understood solely as the acquisition of scientifically correct knowledge. It must also involve mechanisms that regulate the competition between intuitive and scientific responses. In this regard, inhibitory control has been increasingly recognized as playing a key role in overcoming misconceptions. As noted above, misconceptions can remain available in long-term memory and compete with newly acquired scientific conceptions [44]. When such competition arises, inhibitory control may help learners avoid being misled by intuitive but inappropriate responses [45]. More specifically, inhibitory control enables individuals to suppress dominant and automatic mental representations, including prepotent interference arising from misconceptions [12,46].

A growing body of behavioral research supports the role of inhibitory control in resolving conceptual conflict in science. For example, Potvin and colleagues used a series of sink-and-float tasks to investigate whether different degrees of interference would produce different levels of conflict [6,7]. Their findings showed that participants, despite possessing the relevant scientific knowledge, required more time to evaluate problems involving stronger conceptual conflict. Moreover, response times increased, as the degree of conflict became greater. This pattern suggests that correct responding in such cases requires more than the simple retrieval of scientific knowledge; it also points to the involvement of inhibitory control in suppressing interference from misconceptions.

More direct evidence has come from studies adopting the NP paradigm, particularly in physics education [4,24,27,47]. In the NP paradigm, participants first complete a prime task in which they must respond on the basis of a scientifically appropriate target while ignoring a distractor associated with a misconception. They then complete a probe task in which the previously ignored information becomes relevant. The basic logic is that if a strategy or misconception is inhibited during the incongruent prime, then reactivating it in a subsequent congruent probe should be more difficult than in a neutral condition in which no inhibition was required, resulting in slower or less accurate performance. This pattern is commonly referred to as an NP effect [28,29]. Because it captures the lingering consequences of prior suppression, the NP paradigm offers a more process-sensitive way of inferring whether inhibitory control has been engaged during misconception resolution.

For example, Lin *et al*. [3] applied the NP paradigm to examine whether inhibitory control is involved in overcoming the PVI misconception in kinematics. In their study, the misconception was directly triggered by a simple perceptual cue, namely, two objects appearing at the same position in a pictorial representation. By contrast, the competing scientific conception, namely, that the average velocity of an object undergoing uniform acceleration is equal to the instantaneous velocity at the midpoint of the time interval, required more complex processing, including proportional reasoning. The results showed that participants performed worse on congruent probes, that is, same position and same velocity, when these were preceded by incongruent primes, that is, same position but different velocity, than when they were preceded by neutral primes. This typical NP effect provided evidence that inhibitory control was involved in overcoming the PVI misconception.

Further support for the role of inhibition in conceptual change has also come from educational neuroscience. Neuroimaging studies have shown that problems involving misconception interference are associated with activation in prefrontal regions often linked to inhibitory control, including the anterior cingulate cortex, dorsolateral prefrontal cortex, and ventrolateral prefrontal cortex [5,45,48]. Moreover, these inhibition-related regions appear to be activated more strongly in experts than in novices when they solve problems involving misconceptions, suggesting that scientific expertise may partly depend on the ability to suppress intuitive but inappropriate responses [5,45]. Related evidence further suggests that counterintuitive reasoning in science and mathematics recruits neural systems that overlap with inhibitory control, particularly interference control [49,50]. In addition, an event-related potential study by Zhu *et al*. [51] showed that a common misconception can be activated early in processing to assess the plausibility of incoming information, followed by later retrieval of scientific knowledge for conflict monitoring and inhibitory control. Taken together, these findings support a dynamic view in which misconceptions are activated rapidly and automatically, whereas successful scientific reasoning depends on subsequent inhibitory regulation.

Although these findings provide substantial support for the role of inhibitory control in conceptual change, most studies have examined this process within a single representational format. In other words, the evidence is strong that inhibition may be involved when learners confront misconception interference in a given format, but it remains less clear whether such inhibitory demands are stable across different external representations of the same concept. This limitation is especially important in physics, where learners routinely encounter the same underlying idea through multiple representation forms. The next section therefore considers the role of multiple

representations in physics learning and the possibility that they may repeatedly activate the same misconception across formats.

### C. Multiple representations in physics learning and problem solving

From a cognitive perspective, representations can be understood as external forms through which ideas, relations, or phenomena are encoded, communicated, and made available for reasoning [52]. In physics, representations are indispensable because many entities and relations cannot be directly apprehended without some form of external expression. Accordingly, representations should not be viewed merely as vehicles for presenting information but as epistemic tools that shape how learners interpret physical situations and construct solutions [17,53]. Common external representation forms in physics include verbal or textual representations, visual or graphical representations, and symbolic or mathematical representations [54,55].

The instructional value of multiple representations lies in their complementarity. A substantial body of research has shown that learning with multiple representations can be more effective than learning with a single representation because different formats foreground different aspects of the same underlying concept [56–59]. The Design, Functions, Tasks framework, for example, proposes that multiple representations support learning when they distribute complementary information, constrain misinterpretation, and prompt learners to build deeper conceptual relations across formats [58]. Similarly, multimedia learning theory suggests that meaningful learning is facilitated when learners actively select, organize, and integrate information from verbal and visual channels into a coherent mental model [60]. In physics, these perspectives help explain why diagrams may foreground spatial structure, graphs may make functional relations more salient, and equations may express quantitative dependencies with precision. When learners successfully coordinate such representations, they are better able to construct integrated mental models, connect complementary aspects of a phenomenon, and solve problems more flexibly [54,61–63]. Expert learners, in particular, tend to show greater flexibility in selecting and coordinating representations in response to task demands, which distinguishes them from novices [64].

However, the benefits of multiple representations are not automatic. Their successful use requires representational competence, including the ability to interpret individual formats, translate between them, and recognize how they express the same underlying physical meaning. Many students struggle with these demands. Research has shown that learners may recognize separate representations but still fail to integrate them effectively during problem solving [65]. Moreover, representational difficulties are not evenly distributed across formats. Interpretation and coordination challenges may depend on the target representation itself, indicating that representational fluency develops unevenly [66]. Without adequate instructional support, multiple representations may therefore increase cognitive load rather than reduce it. Such findings suggest that while representational diversity can support learning, it may also create conditions under which misunderstanding is amplified.

One particularly important consequence is the persistence of misconceptions across representations. When learners fail to establish meaningful links among formats, they may rely on salient surface features or on prior intuitive reasoning, leading to systematic errors that recur in different representation formats. For example, students may misinterpret a velocity-time graph as if it directly depicted the path of motion, reflecting a failure to connect graphical features with the relevant physical principles [67]. More broadly, research on representational consistency suggests that misconceptions are often not confined to a single format. Nieminen *et al*. [22] found that students frequently applied the same incorrect reasoning across isomorphic tasks presented in verbal, graphical, and vectorial forms. Similarly, Nieminen [68] showed that students' representational consistency before instruction predicted later learning outcomes, with similar misconceptions appearing across diagrams, equations, and graphs. Related findings from other domains reinforce this conclusion. Ott *et al*. [69], for example, showed that students often reproduced consistent errors across formulas and explanatory text, especially when they struggled to reconcile the underlying conceptual relations. Taken together, these studies indicate that misconceptions can be systematic across representational forms rather than being tied to one isolated mode of presentation.

This cross-representation persistence raises an important question for research on inhibitory control. If the same misconception can be repeatedly activated in different formats, then learners may need to repeatedly regulate interference from that misconception as they move across representations. In this sense, the issue of multiple representations is not only a matter of representational competence but also a matter of inhibitory control. Preliminary evidence has begun to address this possibility. For example, Hong *et al*. [24] found accuracy-based interference effects in both tabular and pictorial formats, suggesting that misleading intuitive responses may arise across representations. However, because a response-time-based Stroop effect appeared only in the pictorial format, it remains unclear whether this difference reflected inhibitory control itself or broader differences in task difficulty, perceptual salience, and cognitive load [70,71]. This limitation is important because representational differences may affect not only whether a misconception is activated but also how detectable its inhibitory

regulation becomes. To clarify this issue, further research is needed that compares representations that are more similar in perceptual and processing demands, such as stroboscopic pictures and position-time graphs, so that the role in inhibitory control can be examined under more controlled conditions.

### D. Visual attention allocation on misconception-related features and inhibitory control

Eye tracking has become an increasingly valuable method in physics education research, especially in representation-rich assessment contexts [72,73]. Its value lies in its ability to provide process-level evidence about how learners visually engage with task information during problem solving. Different eye-movement measures offer complementary windows into cognition. Fixations reflect relatively stable gaze patterns, whereas saccades indicate rapid shifts of attention between locations [72,74]. According to the eye-mind assumption [75], the fixation count provides information about how attention is distributed across different parts of a stimulus, whereas fixation duration reflects the depth of processing and cognitive engagement at specific locations [75–77]. First saccades are particularly informative because they index initial attentional orientation [78]. Taken together, these measures make it possible to examine whether learners are initially drawn to misconception-related features, how attention is redistributed during processing, and how much attentional effort is invested in resolving conceptual conflict and inhibiting misconception.

In science and physics education, eye tracking has been widely used to investigate how students interpret representations and solve research-based inventory tasks. For example, Han *et al*. [79] examined students' eye movements in web-based Force Concept Inventory tasks and found that, although more attention was directed toward expert-preferred options after instruction, naive options continued to attract substantial gaze. Becker *et al*. [80] further showed that gaze patterns on solution-relevant and solution-irrelevant areas improved the prediction of response accuracy on selected Test of Understanding Graphs in Kinematics items. Together, these studies indicate that visual attention provides an informative window into students' reasoning processes and conceptual understanding.

More specifically, eye tracking has begun to clarify how misconception-related features capture attention during science problem solving. In many tasks, scientifically relevant information coexists with features that can trigger intuitive but incorrect reasoning. Eye-movement measures therefore offer a way to determine whether misleading information captures attention and how strongly it influences subsequent processing. For example, Wang *et al*. [81] found that when students judged the force exerted by a crane's cable on an object moving at constant speed, they devoted substantial fixation time to the misleading feature of speed, even though correct reasoning depended on attending to the object's weight. Similarly, Madsen *et al*. [82] showed that, when solving conceptual physics problems with diagrams, correct solvers spent more time looking at thematically relevant areas, whereas incorrect solvers spent more time on areas consistent with novicelike reasoning. Together, these studies suggest that eye tracking can reveal how misconception-related features compete with scientifically relevant information during physics problem solving.

Eye tracking is also particularly useful for clarifying the relation between attention and inhibitory processing. Olk [26] showed in a numerical comparison task that participants were more likely to direct their first saccades toward a misleading but salient feature in incongruent trials than in congruent trials, and also exhibited longer fixation durations under incongruent conditions. Related evidence from Galili *et al*. [25] further suggested that misconception-related processing may be accompanied by greater cognitive effort, reflected in indices such as pupil dilation and attentional shifting, even when fixation location differences are less apparent. In physics learning, Wen *et al*. [27] found that previously inhibited misconception-related cues influenced subsequent attentional allocation in a negative priming task. Similarly, Xiong *et al*. [47] reported that novices solving buoyancy problems showed more revisits and less efficient scan paths than experts, suggesting greater difficulty in regulating attention during misconception-related reasoning. Taken together, these studies suggest that eye tracking is useful not only for identifying attention to misleading features but also for revealing how attentional allocation relates to inhibitory processing during conceptual change. However, one important issue remains insufficiently examined. Existing studies on inhibition have mainly focused on overall differences in fixation patterns between congruent and incongruent conditions, rather than directly tracing how attention is allocated to misconception-related features during the inhibitory process itself.

## III. THE CURRENT STUDY

Although prior studies suggest that misconceptions may persist across representation formats [22,69], it remains unclear whether the inhibitory processes involved in overcoming them operate similarly across representations. The present study addresses this issue by focusing on the PVI misconception in position-time ($x$–$t$) graph representations. Prior research has already shown that inhibitory control is involved in overcoming this misconception in stroboscopic representations [3]. However, whether similar inhibitory demands also arise in another visual representation of the same underlying concept remains unresolved. This question is theoretically important because it bears on whether the suppression of a persistent

misconception reflects a more general mechanism across closely related visual representations, rather than an effect tied to one specific representational form.

To investigate this issue, the present study combines an NP paradigm with eye tracking. The NP paradigm provides a process-sensitive way to infer whether a misconception has been actively inhibited by examining whether prior suppression impairs subsequent performance when the previously inhibited information becomes response relevant [4,27,47]. Eye tracking complements this behavioral approach by revealing how attention is allocated to misconception-related and scientifically relevant features during problem solving. In particular, it allows us to examine whether learners initially orient toward misconception-related cues, how attention is subsequently redistributed, and whether prior inhibition influences later attentional allocation [27,47].

This design serves two purposes. First, it enables us to test whether inhibitory control is involved in overcoming the PVI misconception in position-time graph representation tasks. Second, it allows us to examine how visual attention allocation unfolds during this process, thereby clarifying the relation between attentional bias and inhibitory regulation. Accordingly, the present study is guided by the following research questions:

RQ1. Is inhibitory control involved in overcoming the PVI misconception in position-time graph representations?

RQ2. How is visual attention allocated to misconception-related and scientifically relevant features during the inhibition of the PVI misconception?

RQ3. Does prior inhibition of misconception-related information in the prime influence subsequent attentional allocation in the probe?

To address these questions, we conducted two complementary studies. Study 1 examined whether inhibitory control is involved in overcoming the PVI misconception in $x$–$t$ graphs among high school students. Using an NP paradigm, this study aimed to establish whether the behavioral signature of prior inhibition, namely, lower performance on congruent probes following incongruent primes, could also be observed when the misconception was elicited in a graph-based representation. In this way, Study 1 served as an initial test of whether inhibitory control is engaged in resolving the PVI misconception in $x$–$t$ graphs at the secondary school level.

Study 2 extended this investigation to undergraduate physics majors and incorporated eye tracking in addition to the NP paradigm. While Study 1 focused on behavioral evidence of inhibitory control, Study 2 was designed to examine the attentional processes associated with misconception inhibition more directly. Specifically, it allowed us to investigate whether learners initially orient toward misconception-related features in $x$–$t$ graphs, how attention is subsequently redistributed toward scientifically relevant information, and whether prior inhibition in the prime influences attentional allocation in the probe. By combining behavioral and eye-movement evidence, Study 2 provides a more process-sensitive account of how the PVI misconception is activated and overcome.

## IV. STUDY 1: A BEHAVIORAL STUDY OF INHIBITORY CONTROL IN OVERCOMING THE POSITION-VELOCITY INDISCRIMINATION MISCONCEPTION IN POSITION-TIME GRAPHS

### A. Method

#### 1. Participants

*A priori* power analysis was conducted using G * Power 3.1.9.7 to determine the minimum sample size required for a two-level within-subject design analyzed with a paired-samples $t$ test. The analysis indicated that at least 34 participants would be required to detect a medium effect size of 0.50 with 80% power at an alpha level of 0.05 [4,27]. To ensure adequate statistical power and allow for potential exclusions, 45 high school students were recruited from a secondary school in Guangzhou, China, for Study 1. The final sample comprised 45 Grade 10 students, including 22 males and 23 females. All participants had completed prior instruction in kinematics, including the interpretation of position-time graphs, before taking part in the study. They had normal or corrected-to-normal vision.

#### 2. Materials

The task content was conceptually parallel to that used in the previous stroboscopic representation context [3], but all stimuli in the present study were constructed in the form of $x$–$t$ graphs. Specifically, the stimuli required participants to judge the time point at which two trains had the same speed on the basis of their $x$–$t$ graphs. As shown in Fig. 1, three types of items were constructed: incongruent primes, neutral primes, and congruent probes. In the incongruent items, the graphs were designed so that the two objects occupied the same position at a certain moment while differing in speed, thereby eliciting the PVI misconception that same position implies same speed. In the neutral items, no salient position-based cue was available to trigger the PVI misconception. In the congruent items, the two objects had the same speed at the target time point, making the misconception consistent with the correct response.

These items were then combined into four types of prime-probe pairs, including one control condition, one test condition, and two filler conditions. In the control condition, a neutral prime was followed by a congruent probe. In the test condition, an incongruent prime was followed by a congruent probe. In addition, two separate filler conditions were included to reduce participants'

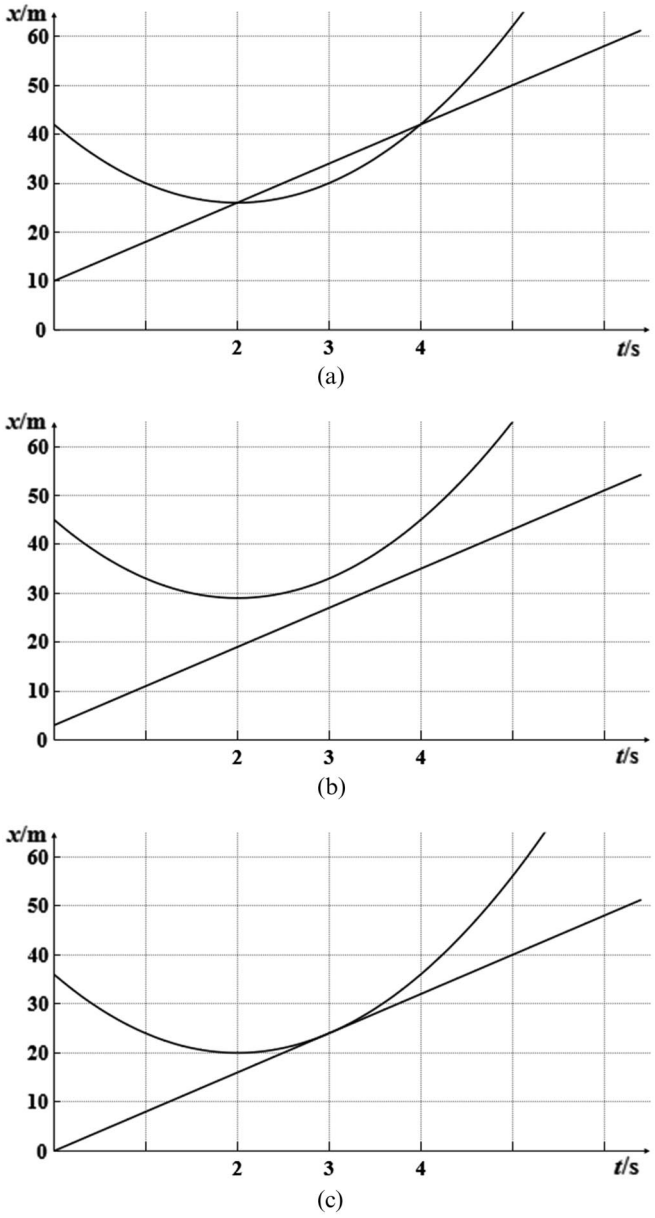



FIG. 1. Examples of the (a) incongruent, (b) neutral, and (c) congruent items used in the negative priming paradigm. The correct response was 3 s.

awareness of the experimental purpose and minimize response expectancy: in one filler condition, a neutral prime was followed by an incongruent probe, whereas in the other filler condition, an incongruent prime was followed by an incongruent probe. Each of the four conditions contained 12 prime-probe pairs, yielding a total of 48 prime-probe pairs for each participant. Across the full set of 48 prime-probe pairs, participants encountered 24 neutral prime items, 24 incongruent prime items, 24 congruent probe items, and 24 incongruent probe items.

Before the formal experiment, the validity of the items was evaluated by six physics teachers. They confirmed that the materials were appropriate for assessing students' understanding of kinematics, particularly the concept of velocity, in $x$–$t$ graph contexts.

### *3. Procedure*

Each participant completed all tasks individually in a quiet computer laboratory. The trials were presented on a computer screen using *E-Prime* 3.0 software (Psychology Software Tools, Inc., Pittsburgh, PA, USA).

At the beginning of the experiment, participants were provided with detailed instructions. They were instructed to press one of the keys D, F, or G on a standard keyboard using their dominant hand, corresponding to 2, 3, and 4 s, respectively. Participants were asked to respond as quickly and accurately as possible. The mapping between keys and time points was counterbalanced across stimuli.

Each trial began with a fixation cross presented at the center of the screen for 500 ms, followed by a prime stimulus consisting of an $x$–$t$ graph representing the motion of two objects. Participants were required to determine the moment at which the two objects had equal instantaneous velocities. After they provided a response, another fixation cross was presented for 500 ms, followed by a probe stimulus with the same task requirement. Participants again selected the corresponding time point by pressing the appropriate key. After responding to the probe, a visual white-noise mask was displayed for 3000 ms to minimize potential carryover effects between trials. The experiment consisted of prime-probe pairs under four conditions, presented in a randomized order. The NP paradigm procedure is illustrated in Fig. 2.

To ensure that participants understood the task requirements, they completed four practice trials with feedback before the formal experiment. These practice trials differed from those in the formal experiment but maintained the same structure and task requirements. The practice trials included one pair from the control condition, one pair from the test condition, and two pairs from the filler conditions. The order of prime-probe pairs was randomized, and none of the practice items appeared in the formal experiment. The purpose of the practice trials was to familiarize participants with the experimental procedure, the visual format of the stimuli, and the response method. Participants proceeded to the formal experiment only after demonstrating that they could correctly perform the velocity-comparison task.

### *4. Data analysis*

Mean ACC and RT were first calculated separately for prime and probe items for each participant under the test and control conditions. Condition-level means were then averaged across participants to obtain the overall descriptive statistics. All inferential analyses were conducted on each participant's mean performance in each condition.

For probe items, ACCs and RTs were calculated only from trials in which the preceding prime had been

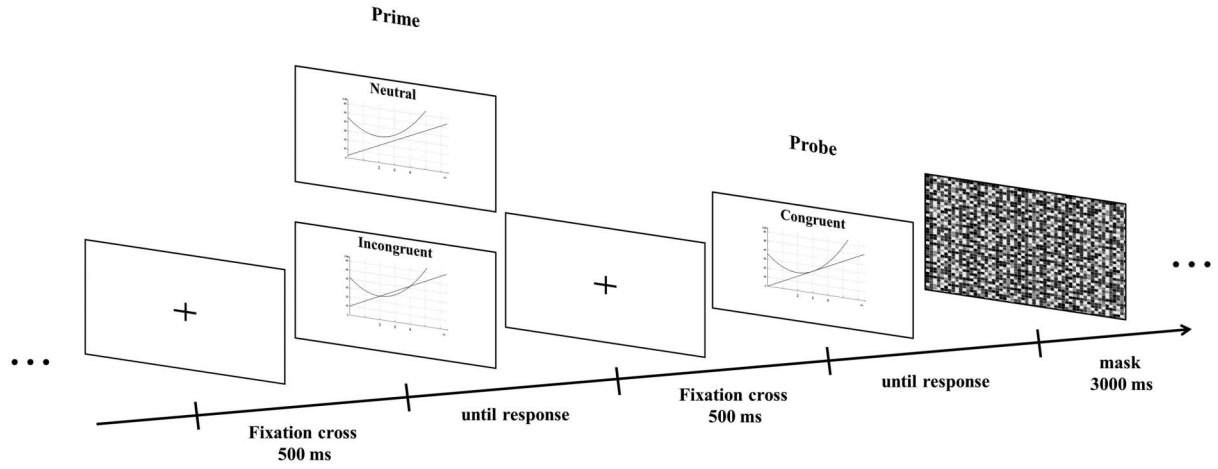



FIG. 2. Experimental trials and procedure of the NP paradigm.

answered correctly, because an incorrect prime response may indicate failure to inhibit the misconception and therefore cannot provide valid evidence for an NP effect [4,27]. Following the procedure reported by previous studies [27,83], RTs that deviated by more than three standard deviations from each participant's mean within each condition were excluded from further analysis. Across conditions, the average proportion of retained trials ranged from 87.4% to 94.3% in Study 1.

Because the study used a within-subject design, normality was evaluated on the paired difference scores rather than on each condition separately. Shapiro–Wilk tests indicated significant deviations from normality for the ACC and RT difference scores. Accordingly, Wilcoxon signed-rank tests were used for the ACC comparisons. RTs were natural log-transformed prior to analysis to reduce skewness, and paired-samples $t$ tests were then conducted on the transformed data. Effect sizes for the RT analyses were estimated using Cohen's $d$.

### B. Results

Table I presents the mean ACC and RT for the neutral and incongruent prime items, as well as for the subsequent congruent probe items, in the $x$–$t$ graph task. For the prime items, the results showed that there was no significant difference in accuracy between the neutral prime condition (95.5%) and the incongruent prime condition (95.9%), Wilcoxon $W = 115.50$, $p = 1.000$. Likewise, there was no significant difference in reaction time between the neutral prime condition (1810 ms) and the incongruent prime condition (1855 ms), $t(44) = 0.916$, $p = 0.364$.

TABLE I. ACCs and RTs for neutral and incongruent prime items and congruent probe items following each prime condition in Study 1(standard errors in parentheses).

| | Prime | | Congruent probe | |
|---|---|---|---|---|
| Prime type | ACC (%) | RT (ms) | ACC (%) | RT (ms) |
| Neutral | 95.5 (1.4) | 1810 (133) | 98.0 (1.0) | 1377 (108) |
| Incongruent | 95.9 (1.1) | 1855 (103) | 93.7 (1.9) | 1665 (242) |

For the probe items, the results showed that the mean accuracy of probes following neutral primes (98.0%) was significantly higher than that of probes following incongruent primes (93.7%), Wilcoxon $W = 72.00$, $p = 0.011$, and rank-biserial correlation = 0.846. In addition, the reaction time of probes following incongruent primes (1665 ms) was significantly longer than that of probes following neutral primes (1377 ms), $t(44) = 2.830$, $p = 0.007$, and Cohen's $d = 0.422$. Taken together, these results indicate a typical NP effect in the $x$–$t$ graph task.

### C. Discussion

Study 1 examined whether a behavioral signature of inhibitory control could be observed when Grade 10 students solved $x$–$t$ graph tasks involving the PVI misconception. Importantly, performance did not differ significantly between the neutral and incongruent prime items themselves. This absence of a prime-stage behavioral difference suggests that the interference induced by the misconception was not directly observable at the level of overt prime performance alone. Instead, the critical evidence came from the probe stage: congruent probes were answered less accurately and more slowly when they followed incongruent rather than neutral primes. This pattern constitutes a typical NP effect, suggesting that participants inhibited the misconception-based response during incongruent prime processing and that this prior inhibition impaired subsequent probe performance.

In this way, Study 1 shows that inhibitory control is involved in overcoming the PVI misconception in position-time graphs. At the same time, because Study 1 relied solely on behavioral indicators, it cannot reveal how the two prime types were processed or how prime processing

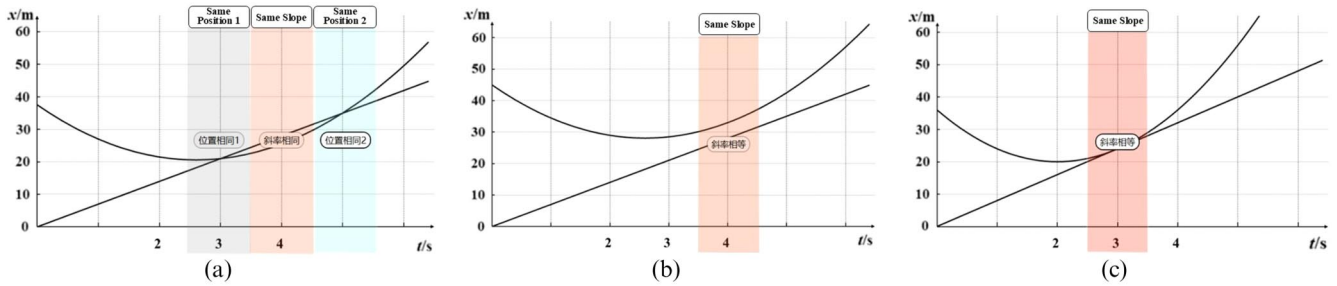



FIG. 3. AOI definitions for incongruent, neutral, and congruent $x$–$t$ graph items. AOI labels: same position 1 (gray), same position 2 (blue), and same slope (orange); panel (c) shows the critical AOI (orange).

shaped subsequent probe performance. Study 2 was therefore designed to examine these issues more directly by combining the NP paradigm with eye tracking and by collecting supplementary post-task reflections about participants' response tendencies.

## V. STUDY 2: AN EYE-TRACKING STUDY OF INHIBITORY CONTROL IN OVERCOMING THE POSITION-VELOCITY INDISCRIMINATION MISCONCEPTION IN POSITION-TIME GRAPHS

### A. Method

#### *1. Participants*

Following the same *a priori* power analysis reported in Study 1, 37 undergraduate physics majors (18 females) from South China Normal University were recruited for Study 2, exceeding the minimum required sample size. All participants had received compulsory physics education in both secondary school and university. In addition, after completing the task, they were asked to define velocity and explain how velocities should be compared. All participants provided scientifically appropriate responses, further supporting the validity of the task for this sample. All were native Chinese speakers, right-handed, and had normal or corrected-to-normal vision, with no reported color blindness or history of psychiatric disorders. Eye-movement data quality was assessed based on the proportion of usable gaze samples. Following previous eye-tracking studies that adopted a 75% criterion for gaze data completeness or tracking quality [84,85], participants with at least 75% usable gaze samples were included in the eye-tracking analyses. All 37 participants met this criterion, and the average proportion of usable gaze samples was 90.89%.

#### *2. Materials*

Study 2 used the same $x$–$t$ graph materials and negative priming paradigam as those described in Study 1. Specifically, the stimuli included neutral prime items, incongruent prime items, and congruent probe items, which were arranged into the same four prime-probe pairing conditions. In addition to the behavioral task, areas of interest (AOI) were defined for the eye-tracking analyses to examine how participants allocated attention to graph features associated with either the PVI misconception or the scientifically correct judgment of equal velocity.

Figure 3 illustrates the AOI definitions for the incongruent, neutral, and congruent items. For the incongruent items [Fig. 3(a)], three AOIs were defined. Two same-position AOIs, shown in gray and blue, corresponded to regions where the two objects occupied the same position but differed in slope. Because these regions were likely to elicit the PVI misconception that equal position implies equal speed, they were treated as misconception-related AOIs. The same-slope AOI, shown in orange, corresponded to the region where the two graphs had equal slope. Because equal slope in an $x$–$t$ graph indicates equal velocity, this region was treated as the scientifically relevant AOI. For the neutral items [Fig. 3(b)], no salient same-position cue was present, so only the same-slope AOI, shown in orange, was defined. For the congruent items [Fig. 3(c)], the same position and same-slope cues overlapped. Accordingly, this overlapping region, shown in orange, was defined as a single critical AOI.

#### *3. Procedure*

The formal experimental procedure in Study 2 was the same as that in Study 1, except that eye movements were recorded throughout the task. Eye-movement data were collected using a Tobii X60 eye-tracking system, which integrates stimulus presentation, eye-movement recording, and data analysis. The system consisted of a screen-based eye tracker and two monitors: one used to present the experimental stimuli and the other used by the experimenter to monitor and record eye-movement data. The stimulus display was presented on a 21-inch monitor with a resolution of $1920 \times 1080$ pixels, and eye-movement data were sampled at 60 Hz. A standard nine-point calibration procedure was conducted before the formal experiment to ensure accurate gaze recording. Participants then completed practice trials to familiarize themselves with the task procedure, stimulus format, and response requirements. During the experiment, both

behavioral responses and eye-movement data were recorded simultaneously.

After the practice trials, participants completed a brief preexperimental session in which they were asked to verbally explain how they judged the velocity of the two objects in the position-time graphs. This procedure was used to confirm that participants understood that velocity should be judged from the slope of the graph rather than from the instantaneous position of the object.

After the entire experiment, participants were shown representative items corresponding to the neutral and incongruent conditions, using the examples presented in Figs. 1(a) and 1(b) rather than the technical condition labels. They were then invited to reflect on the cognitive processes involved in solving these two types of items. These postexperiment reflections were used as supplementary response process evidence.

#### 4. Data analysis

The behavioral analyses of ACC and RT followed the same procedure as in Study 1 and are therefore not repeated here. Across conditions, the average proportion of retained trials ranged from 86.0% to 94.2% in Study 2. Additional between-group comparisons showed no significant differences in retained-trial counts for any of the four conditions, all $ps \geq .078$.

In addition to the behavioral measures, Study 2 included eye-tracking analyses for both the prime and probe stages. The predefined AOIs were used to derive fixation duration, fixation count, and time to first fixation. Fixation duration was defined as the total duration of all valid fixations falling within a given AOI during the stimuli interval and was used as an index of sustained visual attention to, and potentially deeper processing of, the corresponding AOI [86–88]. Fixation count was defined as the number of valid fixations within a given AOI and was used to indicate how frequently participants returned to or sampled information from that AOI [86,87]. Time to first fixation was defined as the latency from stimulus onset to the first valid fixation within a given AOI [89,90]. Following prior eye-tracking research, this measure was used as a temporal indicator of early attentional orienting to the AOI [27,87,88]. In the present task, a shorter time to first fixation to the same-position AOI was taken to indicate earlier orientation to the perceptually salient position cue, whereas shorter time to first fixation to the same-slope AOI was taken to indicate earlier orientation to the scientifically relevant velocity cue. This interpretation was made cautiously because early gaze allocation may reflect both bottom-up salience and top-down task goals [88,91].

For the prime stage, analyses focused on the predefined AOIs in the neutral and incongruent prime items. Specifically, fixation duration, fixation count, and time to first fixation on the same-slope AOI were compared between the neutral and incongruent prime conditions. In addition, within the incongruent prime condition, time to first fixation was compared between the same-position AOIs and the same-slope AOI. For the probe stage, analyses focused on the congruent probe items following neutral and incongruent primes. Fixation duration, fixation count, and time to first fixation on the critical AOI were compared between the two preceding primes.

Because the study used a within-subject design, normality was assessed on the paired difference scores rather than on each condition separately. Shapiro–Wilk tests indicated significant non-normality in the behavioral difference measures and in the eye-tracking difference measures. Accordingly, accuracy and fixation count were analyzed using Wilcoxon signed-rank tests. Reaction time, fixation duration, and time to first fixation were natural log-transformed prior to analysis, and paired-samples $t$ tests were then conducted on the transformed data. Effect sizes for the $t$ test analyses were estimated using Cohen's $d$.

### B. Results

#### 1. Behavioral results

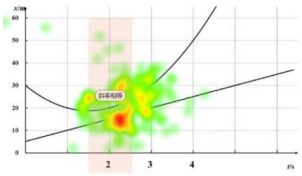
Table II presents the mean ACC and RT for the neutral and incongruent prime items, as well as for the subsequent congruent probe items, in Study 2. Analyses of the prime items showed that there was no significant difference between the neutral and incongruent prime conditions in either ACC, Wilcoxon $W = 63.00$, $p = 0.811$, or RT, $t(36) = 0.268$, $p = 0.790$. Likewise, the ACC of the congruent probe items did not differ significantly between the two conditions, Wilcoxon $W = 4.00$ and $p = 0.850$. However, the RT for congruent probes following incongruent primes was significantly longer than that for congruent probes following neutral primes, $t(36) = 4.289$, $p < 0.001$, and Cohen's $d = 0.705$. This pattern indicates a typical NP effect.

#### 2. Eye-movement results for primes

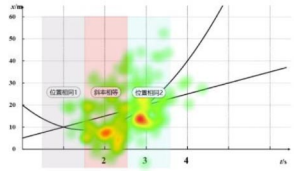
Figure 4 presents the heatmaps and eye-movement measures for the neutral and incongruent primes. As shown in the representative heatmaps in Figs. 4(a) and 4(b), participants allocated substantial attention to the same-slope AOI in both conditions. To examine whether attention to the same-slope AOI differed between the two prime

TABLE II. ACCs and RTs for neutral and incongruent prime items and for congruent probe items following each prime condition in Study 2 (standard error in parentheses).

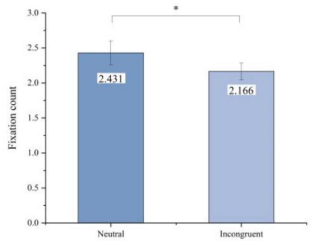
| | Prime | | Congruent probe | |
|---|---|---|---|---|
| Prime type | ACC (%) | Prime RT (ms) | ACC (%) | RT (ms) |
| Neutral | 97.2 (0.8) | 1740 (108) | 99.3 (0.4) | 1052 (32) |
| Incongruent | 97.3 (1.0) | 1714 (100) | 99.7 (0.3) | 1164 (39) |



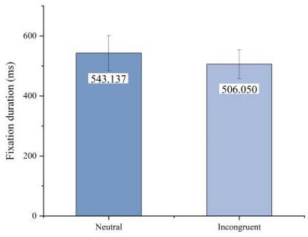
(a) Heatmap for the neutral primes.



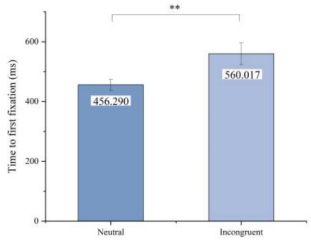
(b) Heatmap for the incongruent primes.



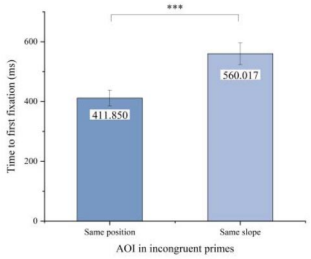

(c) Fixation count on the same slope AOI in the neutral and incongruent prime conditions.




(d) Fixation duration on the same slope AOI in the neutral and incongruent prime condition




(e) Time to first fixation on the same slope AOI in the neutral and incongruent prime conditions.




(f) Time to first fixation on the same position AOIs and the same slope AOI within the incongruent prime condition.

FIG. 4. Heatmaps and eye-movement measures for the prime items. *Note*. Error bars represent standard errors of the mean. $^{**}p < 0.001$. $^{*}p < 0.01$. $^{*}p < 0.05$.

conditions, paired comparisons were conducted on fixation count, total fixation duration, and time to first fixation.

The results showed that the fixation count on the same-slope AOI was significantly greater for neutral primes than for incongruent primes (2.431 vs 2.166), Wilcoxon $W = 460.00$, $p = 0.047$, and rank-biserial correlation = 0.381, as shown in Fig. 4(c). By contrast, fixation duration on the same-slope AOI was numerically longer for neutral primes than for incongruent primes (543 vs 506 ms), but this difference was not significant, $t(36) = 0.545$, $p = 0.589$, as shown in Fig. 4(d).

To further examine the temporal dynamics of processing, the time to first fixation on the same-slope AOI was compared between the two prime conditions. Participants entered the same-slope AOI significantly later in the incongruent primes than in the neutral primes (560 vs 456 ms), $t(36) = 2.730$, $p = 0.010$, Cohen's $d = 0.449$, as shown in Fig. 4(e). This result suggests that the presence of the same-position cue in the incongruent items delayed initial access to the graph region that supported the scientifically correct velocity judgment.

Importantly, the heatmap for the incongruent primes [Fig. 4(b)] also showed clear attention to the same-position AOIs. To test whether these AOIs attracted attention earlier than the same-slope AOI, the time to first fixation was compared between these two AOI types within the incongruent primes. The results showed that participants fixated the same-position AOIs significantly earlier than the same-slope AOI (412 vs 560 ms), $t(36) = -4.648$, $p < 0.001$, Cohen's $d = 0.764$, as shown in Fig. 4(f).

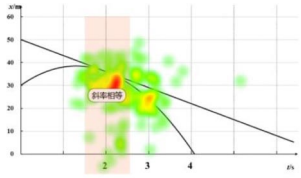
The postexperiment reflections provided supplementary qualitative evidence consistent with this pattern. Participants' accounts indicated that the intersection points in the incongruent items tended to attract attention, whereas solving the neutral items could require additional visual search to identify the point of equal slope. For example, one participant reported that "the intersection point attracted my attention," whereas for the neutral item,

the participant searched for "the point at which the distance between the two graphs was the largest" as a cue for locating equal slope. These reflections suggest that the two prime types involved different visual processing demands and that the neutral items were not necessarily an effortless baseline, which may help explain the absence of a significant prime reaction time difference. A representative interview excerpt illustrating these response patterns is provided in the Appendix.

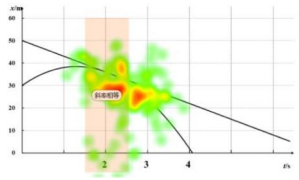
### *3. Eye-movement results for the probes*

Figure 5 presents the heatmaps and eye-movement measures for the congruent probe items following neutral and incongruent primes. Visual inspection of the heatmaps suggests that when a congruent probe followed an incongruent prime [see Fig. 5(b)], participants also devoted noticeable attention to regions outside the critical AOI, including areas that spatially corresponded to the same-position AOIs in the preceding prime.

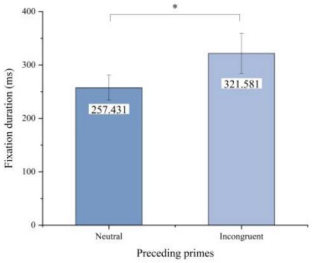
To determine whether prior-prime type influenced attentional allocation during probe processing, eye-movement measures on the critical AOI were compared between the two probe conditions. The results showed that fixation duration on the critical AOI was significantly longer when the probe followed an incongruent prime than when it followed a neutral prime (322 vs 257 ms), $t(36) = 2.507$, $p = 0.017$, Cohen's $d = 0.412$, as shown in Fig. 5(c). Similarly, the fixation count on the critical AOI was numerically greater in probes following incongruent primes than in probes following neutral primes (1.58 vs 1.40), although this difference did not reach statistical significance, Wilcoxon $W = 227.00$, $p = 0.061$, and rank-biserial correlation = 0.354, as shown in Fig. 5(d). In addition, the time to first fixation on the critical AOI was significantly later when the probe followed an incongruent



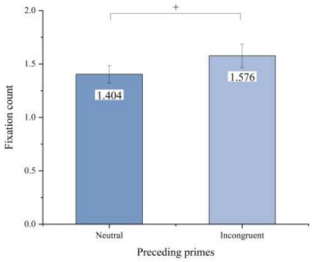
(a) Heatmap for congruent probes following neutral primes.



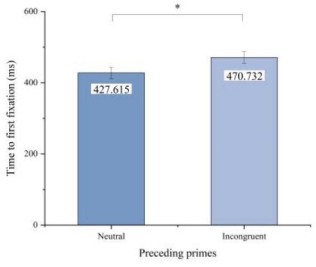
(b) Heatmap for congruent probes following incongruent primes.




(c) Fixation duration on the critical AOI for congruent probes following neutral and incongruent primes.




(d) Fixation count on the critical AOI for congruent probes following neutral and incongruent primes.




(e) Time to first fixation on the critical AOI for congruent probes following neutral and incongruent primes.

FIG. 5. Heatmaps and eye-movement measures for the probe items. *Note*. Error bars represent standard errors of the mean. $*p < 0.05$. $+p < 0.10$.

prime than when it followed a neutral prime (471 vs 428 ms), $t(36) = 2.143$, $p = 0.039$, Cohen's $d = 0.352$, as shown in Fig. 5(e).

Overall, the probe-stage eye-movement results indicate that prior processing of an incongruent prime influenced subsequent attentional allocation in the congruent probe. Specifically, prior inhibition was associated with later entry into the critical AOI and greater attentional investment once that AOI was fixated. Although the difference in fixation count did not reach significance, the pattern of fixation duration and time to first fixation suggests that inhibitory processing in the prime carried over to the probe stage and continued to shape subsequent visual processing during reasoning.

### C. Discussion

Study 2 replicated the behavioral NP effect observed in Study 1 and further clarified the attentional processes associated with that effect. Behaviorally, congruent probes were responded to more slowly when they followed incongruent rather than neutral primes, providing further evidence that overcoming the PVI misconception in *x–t* graphs involved inhibitory control.

Importantly, Study 2 also helps clarify the interpretation of Study 1. Although Study 1 revealed no significant behavioral difference between neutral and incongruent primes, the eye-tracking results of Study 2 showed that the two prime types were not processed in the same way. During incongruent prime processing, participants entered the same-position AOIs earlier than the same-slope AOI, while entry into the same-slope AOI was delayed relative to the neutral condition. This pattern suggests that the misconception-consistent cue captured attention early and temporarily interfered with access to the graph feature that supported the scientifically correct response. The probe-stage results further showed that congruent probes following incongruent primes elicited later entry into, and greater fixation duration on, the critical AOI, indicating that prior-prime processing continued to influence subsequent visual processing. In addition, participants' post-task reports provided supplementary process-based support for this interpretation by indicating that the same-position cue in the incongruent items tended to attract attention, whereas the neutral items required additional visual search to locate the point of equal slope. Taken together, Study 2 shows not only that inhibitory control is involved in *x–t* graph reasoning but also that this process is closely associated with the allocation of visual attention during both prime and probe processing.

## VI. GENERAL DISCUSSION

The present research examined whether inhibitory control is involved in overcoming the PVI misconception in position-time (*x–t*) graph representations and whether this process is reflected in visual attention allocation. Across two studies, the findings provide converging support for three main points. First, both studies yielded a typical NP effect, such that performance on congruent probes was impaired when they followed incongruent rather than neutral primes. This pattern indicates that overcoming the PVI misconception in *x–t* graphs required the prior suppression of a misleading intuitive response. Second, Study 2 showed that, during incongruent prime processing, participants entered the same-position AOIs earlier than the same-slope AOI, suggesting that the misconception-related cue captured attention at an early stage of processing. Third, prior inhibition shaped subsequent attentional allocation in the probe stage, as reflected in later entry into, and greater attentional investment on, the critical AOI following incongruent primes. Taken together, these findings suggest that the PVI misconception is activated early, competes for attentional resources, and requires inhibitory control in order for scientifically appropriate reasoning to prevail.

These findings support a coexistence view of conceptual change, according to which misconceptions and scientific conceptions may remain simultaneously available rather than one fully replacing the other [7,14,41,42]. In both studies, participants had already received relevant instruction and demonstrated that they could define velocity appropriately. Nevertheless, the PVI misconception still produced reliable interference. This pattern suggests that the difficulty did not arise from a simple lack of knowledge. Rather, it reflected competition between a perceptually compelling but misleading cue and the scientifically correct basis for judging velocity. In this sense, the present findings extend previous work showing that misconceptions can remain cognitively robust even after learners acquire formal scientific understanding [3–6].

More specifically, the results strengthen the argument that inhibitory control plays a key role in overcoming misconceptions. A growing body of research has shown that correct responding in counterintuitive science tasks often depends on suppressing prepotent but inappropriate responses [3,4,6,11,45,51]. The present study adds to this literature by showing that such inhibitory demands are also present in *x–t* graph reasoning. Study 1 established this point behaviorally in high school students, whereas Study 2 replicated the NP effect in physics majors and further revealed how the process unfolded in visual attention. The convergence of the two studies suggests that inhibitory control is involved not only when learners interpret motion in more pictorial forms [3] but also when they reason with more formal graphical representations of the same concept.

At the same time, the present findings sharpen the question of whether inhibitory control may operate across different representations of the same concept. Prior work had already shown that inhibitory control was involved in

overcoming the PVI misconception in stroboscopic representations [3]. The present results show that a similar inhibitory pattern also arises in $x$–$t$ graphs, suggesting that the suppression of the PVI misconception is not confined to a single external representational format. This interpretation is broadly consistent with earlier research showing that students often reproduce the same incorrect reasoning across isomorphic tasks presented in different representational formats [22], which implies that some misconceptions are robust enough to recur across contexts. One possible explanation is the generality of the underlying intuitive rule. From the perspective of intuitive rules theory, misconceptions may persist across representations because learners are not merely responding to the surface features of a single format but are instead applying the same deeply rooted heuristic across contexts. [39,40]. In the present case, the PVI misconception may reflect a rule such as "same A, same B": if two objects share the same position, they are assumed to share the same speed. Such intuitive rules are highly general and may be activated whenever a task contains a cue that fits the underlying pattern, even when the representation changes.

This interpretation is also compatible with more recent evidence that interference effects can arise across representations, although not always in identical ways. For example, Hong *et al*. [24] found ACC-based interference in both tabular and pictorial formats, but an RT-based Stroop effect only in the pictorial format, suggesting that representation differences in task difficulty and cognitive load may shape whether inhibitory demands become behaviorally detectable. A complementary explanation concerns the relative generality of inhibitory control itself. According to conflict monitoring theory, conflict detection triggers an upregulation of inhibitory control that is not necessarily tied to a specific stimulus format but may operate at a more general level when the same competing responses are involved [92]. From this perspective, if different representations evoke the same intuitive response and the same scientific response, similar inhibitory demands may arise across formats because what carries across representations is not the perceptual form itself, but the need to suppress the same misleading response tendency in favor of the same scientifically appropriate one. Against this background, the present study contributes by extending prior evidence from stroboscopic tasks to $x$–$t$ graphs, two representations that are both visual and conceptually close to one another. In this sense, the findings provide initial evidence that inhibitory control may generalize across closely related visual representations in overcoming misconceptions.

The present study also clarifies that inhibitory control in conceptual change is closely linked to visual attention allocation. During the prime stage, participants entered the same-position AOIs earlier than the same-slope AOI, indicating that the misconception-related cue attracted attention at an early stage of processing. Delayed entry into the same-slope AOI further suggests that this early attentional capture interfered with access to the graph feature that supported the scientifically correct response. This pattern implies that the influence of the misconception begins not only at the level of overt response selection but also at the level of early visual orienting. In this respect, the present findings are consistent with Zhu *et al*. [51], who showed that misconception congruent stimuli elicited an enhanced P2, whereas misconception incongruent stimuli elicited an enhanced N2, suggesting that intuitive misconceptions may be invoked early to evaluate the plausibility of incoming information before later conflict monitoring and inhibition occur. The present results are also compatible with prior eye-tracking work showing that misleading features can attract attention during problem solving [81,82].

During the probe stage, the present study further showed that prior inhibition was associated with later entry into, and greater fixation on, the critical AOI, suggesting that inhibition continued to shape subsequent visual processing. This pattern is broadly consistent with Wen *et al*. [27], who found that previously inhibited misconception-related cues influenced later attentional allocation in an NP task, and with Xiong *et al*. [47], who reported that novices showed more revisits and less efficient scan paths than experts during misconception-related reasoning. Taken together, the present findings support the view that inhibitory control in conceptual change is not a purely late corrective process but is intertwined with the allocation and reallocation of attention from early orienting onward.

The present findings also have important implications for physics instruction. First, they suggest that helping students overcome misconceptions requires more than presenting the correct concept. Instruction may also need to support students in recognizing when cues are likely to mislead them and in shifting attention toward the cues that are scientifically relevant. In the context of $x$–$t$ graphs, this means that teaching should explicitly distinguish position from slope and should guide students to interpret slope as the basis for judging velocity rather than relying on shared position. Second, the findings suggest that multiple representations do not automatically reduce misconception-based interference. Instead, if the same misconception can be activated across different formats, instruction may need to explicitly help students coordinate representations and identify which visual cues are relevant in each case [93].

Several limitations should also be acknowledged. First, the study focused on one specific misconception within one topic area of mechanics. Although the PVI misconception is theoretically and educationally important, it remains unclear whether similar inhibitory and attentional patterns would be observed for other persistent misconceptions in physics. Future research should therefore extend the present paradigm to additional misconceptions

and domains in order to determine how broadly the current findings generalize. Second, the claim that inhibitory control may generalize across representations is based on comparison with prior findings rather than on a direct within-study comparison of multiple formats. As a result, the present study provides only initial evidence for such generality. A more decisive test would require presenting different representations of the same concept within a single experimental design. Third, the two studies involved different participant groups, which limits stronger developmental interpretations or expertise-related interpretations. Although the retained-trial proportions did not differ significantly between the high school students and undergraduate physics majors in any condition, the two groups nevertheless differed in age, educational level, and prior experience with kinematics. These differences were not experimentally controlled because the two studies were designed for complementary purposes rather than as a direct developmental comparison. Future research could address this issue by applying the same behavioral and eye-tracking paradigm to learners at different educational stages within a single design, which would allow the effects of age, prior knowledge, and physics expertise to be examined more directly. Fourth, although eye-tracking measures provide valuable process-level evidence about overt attentional allocation, they remain indirect indicators of cognitive processing. They cannot on their own fully specify covert attention or all components of inhibitory control. Future studies could therefore combine eye tracking with other process-sensitive methods, such as event-related potentials, or other neuroscientific measures in order to provide a more complete account of how misconceptions are activated, regulated, and overcome. In addition, the incongruent graph items contained salient intersections and may also have been more perceptually complex than the neutral items. Thus, differences in prime-stage gaze allocation cannot be attributed exclusively to misconception activation. Although the longer response times on congruent probes following incongruent primes than following neutral primes are consistent with a negative priming and inhibition account, they do not by themselves rule out contributions from differences in visual processing or prime difficulty. Future studies could address this issue by manipulating misconception congruency while more closely matching the perceptual complexity and visual salience of the prime stimuli.

## VII. CONCLUSION

The present study shows that overcoming the PVI misconception in $x$–$t$ graphs involves inhibiting a compelling intuitive response and reallocating attention toward scientifically relevant information. Across two studies, converging behavioral and eye-tracking evidence showed that the PVI misconception is activated early, interferes with processing, and leaves measurable consequences for subsequent performance and attentional allocation. Importantly, by extending prior evidence from stroboscopic representations to position-time graphs, the present research provides initial evidence that the inhibitory demands associated with overcoming the PVI misconception may generalize across closely related visual representations of the same kinematic concept. More broadly, these findings contribute to the growing literature showing that conceptual change depends not only on conceptual knowledge but also on the inhibitory control processes that regulate when and how that knowledge is used.

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## DATA AVAILABILITY

There are no publicly available research data or software supporting this manuscript. Requests for further information or data should be sent to the authors.

## APPENDIX: EXAMPLE INTERVIEW EXCERPT

| | |
|---|---|
| Interviewer: | Looking at the two example items shown in Figs. 1(a) and 1(b), could you describe whether you felt any difference when solving these two types of items? |
| Participant: | The intersection point in Fig. 1(a) attracted my attention. My eyes tended to move toward the intersection point. |
| Interviewer: | For the type of item shown in Fig. 1(b), where there was no intersection point between the two graphs, how did you determine the time at which the two objects had the same velocity? |
| Participant: | I looked for the point at which the distance between the two graphs was the largest. |
| Interviewer: | What exactly do you mean by "the largest distance"? Could you explain how this helped you judge whether the two objects had the same velocity? |
| Participant: | I mean the vertical distance between the curve and the straight line. When this distance becomes the largest, the curve is no longer moving farther away from the straight line and then starts getting closer to it. At that point, I felt that the slope of the |

curve should be the same as the slope of the straight line, so the two objects should have the same velocity.

Interviewer: Compared with the type of item shown in Fig. 1(a), do you think the type of item shown in Fig. 1(b) would be solved more quickly?

Participant: I do not think so. Although the intersection points in Fig. 1(a) attracted my attention and could be interfering, they also made it easier for me to locate the relevant region and judge the time at which the two objects had the same velocity, that is, the same slope.

*Note.* This excerpt suggests that the two item types involved different processing demands. The item shown in Fig. 1(a) contained intersection points that attracted the participant's attention and may have introduced position-based interference. By contrast, the item shown in Fig. 1(b) did not contain such intersection points, but the participant still needed to search for the point of maximum vertical separation and relate it to the equality of slopes. Therefore, the neutral items should not be regarded as a visually effortless baseline. This response process evidence provides a possible explanation for why neutral items were not solved faster than incongruent items.


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