Contextual sensitivity of inhibitory control in physics conceptual change: Evidence from a negative priming study

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Scientific knowledge does not necessarily replace intuitive misconceptions; successful physics reasoning may therefore require learners to control responses that remain cognitively available. However, inhibitory-control accounts have yet to explain whether the same conceptual conflict elicits a stable amount of control across representational contexts or whether control mobilization varies with contextual typicality and physics training. This study addressed this issue using a negative-priming (NP) paradigm in the domain of static friction. High-school students and undergraduate physics majors made static-friction judgments in a prototypical context and a nonprototypical context. Within the inhibitory account adopted here, NP magnitude was interpreted as a behavioral index of the control mobilized during the preceding incongruent prime. Probe-phase reaction times were analyzed on the log scale using a linear mixed-effects model with Group, Context, and Prime Type and their interactions. The analysis revealed a context-dependent pattern of NP, with the magnitude of this contextual modulation differing between the two groups. Specifically, NP was negligible in the prototypical context for both high-school students and physics majors. By contrast, reliable NP emerged in the nonprototypical context. This increase was substantially larger among high-school students than among physics majors. When translated back to the original reaction-time scale, NP in the nonprototypical context corresponded to an approximately 20.77% increase for high-school students, compared with a 5.65% increase for physics majors. Taken together, these findings show that the inhibitory control mobilized by the same conceptual conflict is not fixed across representations. The nonprototypical representation amplified inhibitory-control demand, whereas physics training attenuated this amplification. The training-related advantage is therefore better characterized as reduced contextual sensitivity of inhibitory mobilization than as a context-invariant absence of conceptual conflict. The results advance process-based accounts of conceptual change by linking problem representation, domain knowledge, and task-evoked inhibitory control.

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I. INTRODUCTION

Early accounts of conceptual change often characterized science learning as the restructuring or replacement of prior conceptions [1,2]. However, intuitive conceptions do not necessarily disappear after scientific knowledge has been acquired [3–5]. Both less experienced and more extensively trained learners may remain susceptible to intuitive interference in particular contexts [6,7]. Behavioral and neurocognitive evidence, together with physics education research on dual-process reasoning, cognitive accessibility, and response-time patterns, therefore supports a conceptual-competition account in which successful scientific reasoning involves not only retrieving relevant scientific knowledge but also regulating intuitive responses that remain cognitively available [3–5,8–15].

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Inhibitory control has been proposed as one mechanism through which this conceptual competition is resolved. However, the control required in a particular reasoning episode may depend on how the problem is represented. Research on transfer and physics problem solving has repeatedly shown that learners may successfully apply a principle in a prototypical setting but fail to recognize the same underlying relation when the surface features of a problem change [16–20]. Such findings have generally been explained in terms of knowledge organization, recognition of deep structure, and the availability of contextual cues [21–23]. Less attention has been given to whether representational changes also alter the regulatory processes involved in resolving competition between intuitive and normative responses. When a problem departs from a typical representational structure, learners may need to reconstruct their representation of the context and identify the invariant physical relation beneath altered surface features. These additional requirements may increase demands on working memory and executive control, thereby changing the processing cost associated with regulating intuitive responses [24–26]. Thus, even when learners respond correctly across contexts, the processes through which conceptual conflict is resolved, and the associated processing costs, may differ. It therefore remains unclear whether a given conceptual conflict elicits a stable amount of inhibitory control across representational contexts.

The level of physics training may moderate this contextual sensitivity. Systematic training is associated with more structured domain knowledge and more robust recognition of underlying physical relations across superficially different problems [18,21,22]. Behavioral and neurocognitive evidence further indicates that physics training changes how intuitive interference is regulated, without necessarily eliminating that interference [6–8,10]. More structured representations and more fluent access to relevant physical relations may reduce the extent to which changes in surface representation disrupt scientifically appropriate reasoning. The advantage associated with physics training may therefore lie not in the disappearance of intuitive conceptions, but in reduced vulnerability to the additional regulatory demands imposed by a less typical context. However, most existing evidence has been obtained under a single or relatively familiar task condition. Whether physics training attenuates the contextual modulation of inhibitory-control mobilization remains unclear.

The present study examined this issue using static friction as the target domain. Learners commonly endorse the misconception that increasing the normal force necessarily increases the actual static-friction force [27], although the actual static-friction force is determined by the force required to maintain equilibrium, up to its maximum value. Previous research indicates that judgments involving this misconception are context-dependent: learners generally perform better in prototypical horizontal configurations but are more likely to make incorrect judgments when the same target relation is instantiated in vertical configurations [27–29]. Static-friction problems therefore provide a means of varying contextual typicality while preserving the target physical relation and the misconception-consistent response.

To obtain process-sensitive evidence, we employed a negative-priming (NP) paradigm [30–33]. On an incongruent prime trial, participants were required to reject the intuitive judgment that "the greater the normal force, the greater the actual static-friction force must be." The subsequent probe trial was congruent with this intuitive judgment. Under the inhibitory interpretation of negative priming, suppressing the intuitive response during the incongruent prime should produce a carryover cost when that response must be reactivated on the subsequent probe. Accordingly, responses to an intuition-consistent probe should be slower following an incongruent prime than following a neutral prime. Within the inhibitory account adopted here, NP magnitude was interpreted as a behavioral index of the control mobilized during the preceding incongruent prime [34].

We compared high-school students and undergraduate physics majors in a prototypical horizontal context and a nonprototypical vertical context. The study examined whether NP magnitude varied with contextual typicality and whether this contextual variation differed according to the level of physics training.

II. LITERATURE REVIEW

A. Conceptual competition and inhibitory regulation

A persistent difficulty in physics learning is that the acquisition of relevant scientific knowledge does not guarantee that this knowledge will guide reasoning in every context. Learners may answer incorrectly because the relevant relation has not been constructed, because it is available but insufficiently accessible under the cues provided by the problem, or because it is activated together with a more compelling intuitive response that dominates response selection [11–13,35,36]. These possibilities are theoretically distinct. Knowledge availability concerns whether the learner possesses the relevant conceptual resources; accessibility concerns how readily those resources are activated in a particular task; and regulation concerns how competition is resolved when normative and misconception-consistent responses are simultaneously available. Evidence that scientifically educated individuals remain slower or less accurate when scientific and intuitive knowledge support different answers further indicates that acquiring normative knowledge does not necessarily eliminate earlier intuitions [3–5].

Dual-process accounts provide a useful framework for explaining how this competition can arise. In default-interventionist versions of heuristic-analytic theory, salient

problem features may rapidly activate an initially compelling response, after which further processing may endorse, revise, or replace that response [37–39]. Physics education research has documented an "answer-first" pattern in which learners initially adopt an intuitively available model and subsequently organize an explanation around that model rather than deriving a conclusion from the relevant physical relations [11,12]. Related intervention studies show that modifying task cues, reducing the salience of a misleading model, or increasing the accessibility of the normative relation can shift reasoning toward a scientific response when the requisite knowledge is at least partially available [12,13,40]. Thus, errors in physics reasoning cannot be attributed only to missing knowledge; they may also reflect the task-dependent accessibility and influence of competing representations.

Heckler and colleagues have developed this point by emphasizing the relative processing advantage of alternative reasoning pathways. In science-question tasks, a salient but non-normative pathway may initially be processed more rapidly than the normative pathway, increasing the probability that it determines the response; additional processing time and practice can shift this balance by improving the speed and availability of the normative pathway [14]. The cognitive-accessibility account similarly proposes that, when multiple explanations are available, the explanation that is more readily accessible under the current task conditions is more likely to influence response selection [15]. Longitudinal evidence from mastery practice further shows that learning can increase accuracy while reducing response time, consistent with greater fluency of relevant knowledge and procedures [41]. These findings caution against equating intuition with speed and science with slowness: normative relations can become rapidly accessible through instruction and practice, whereas an intuitive answer can be followed by extended post hoc justification [11,42,43]. The central issue is therefore the relative accessibility and processing advantage of competing responses within a particular task.

When a misconception-consistent response is highly accessible but conflicts with the relevant scientific relation, scientifically appropriate judgment requires that its influence on response selection be reduced. Inhibitory control provides a theoretically important account of this regulatory requirement. Inhibitory regulation refers to interference-control processes that limit the influence of a salient but task-inappropriate intuitive representation or response, thereby allowing the normative physical relation to guide judgment [44–47]. Research across mechanics, buoyancy, and position-velocity reasoning has reported behavioral and neurocognitive patterns consistent with the involvement of inhibitory regulation when learners overcome persistent intuitive conceptions [4,8–10]. More recent work also indicates that inhibition-related costs vary with the familiarity of intuitive conceptions and the complexity of the corresponding scientific relations, suggesting that inhibitory-control mobilization is not fixed but can vary with characteristics of the conceptual conflict [34]. Taken together, this literature supports a conceptual-competition account in which successful physics reasoning depends on both the accessibility of normative knowledge and the regulation of misconception-consistent interference.

B. Context and physics training in conflict processing

The accessibility of a physical relation depends partly on how a problem is represented. Research on transfer and expert-novice problem solving has repeatedly shown that learners may fail to apply a known principle when surface features change, even when the underlying relational structure is preserved [20,23]. More advanced solvers tend to organize problems around underlying physical principles, whereas less experienced solvers are more strongly influenced by objects, configurations, and other surface characteristics [21,22]. Surface features are therefore not merely cosmetic. They provide cues for constructing a situation model, selecting knowledge resources, and determining which physical relations appear relevant.

A prototypical representation can support rapid recognition of a practiced problem structure and efficient retrieval of the associated relation. By contrast, a less typical representation may require additional mental transformation, re-representation, and identification of the invariant relation beneath altered surface features. These demands can consume limited processing resources and disrupt established cue-knowledge mappings [24–26]. Contextual variation may consequently change the relative accessibility of misconception-consistent and normative responses and, in turn, the degree of inhibitory regulation required for scientifically appropriate response selection. On this account, context does not constitute a separate alternative to inhibitory regulation. Rather, it alters the representational and accessibility conditions under which inhibitory regulation must be recruited.

Physics training may reduce this contextual vulnerability by reorganizing both knowledge and processing. Structured domain knowledge supports recognition of deep relations across superficially different problems and enables more selective retrieval of relevant principles [20–22]. Research on relative processing time and cognitive accessibility further suggests that practice can increase the speed with which normative relations become available, thereby improving their likelihood of controlling response selection [14,15,41]. More fluent access to normative relations can therefore reduce the processing demands of conceptual competition, particularly when the problem departs from its prototypical representational form.

Training, however, should not be equated with the disappearance of intuitive conceptions or with immunity to contextual variation. Behavioral and neurocognitive evidence indicates that advanced learners may remain

sensitive to intuitive interference even when they respond correctly [3,8,10,46]. The advantage associated with physics training is therefore better characterized as conditional: more structured representations and more practiced access to normative relations may reduce the inhibitory demand imposed by a nonprototypical context, but they need not eliminate that demand. This account predicts that contextual variation will affect both less and more trained learners, while producing a larger increase in conflict-related processing cost among learners whose knowledge organization and cue-relation mappings are less developed.

C. Negative priming as process evidence

Accuracy alone cannot reveal whether a scientifically correct answer was produced fluently or only after competition between alternative responses. Response time (RT) provides complementary process evidence when it is interpreted through theoretically motivated comparisons between controlled task conditions rather than treated as a direct indicator of intuition or analysis [48–51]. Across scientific-verification and physics-reasoning tasks, responses are commonly slower when intuitive and normative knowledge support different answers than when they converge, including trials on which participants ultimately provide the scientifically correct response [3,4,14]. Such findings indicate that identical levels of accuracy may conceal substantial differences in the processing demands associated with response selection.

The NP paradigm provides a more targeted method for examining whether the consequences of prior inhibitory regulation persist across successive trials [30–33]. On an incongruent prime trial, salient cues activate a misconception-consistent response, but the participant must reject that response and select the normative alternative. On the subsequent probe trial, the previously rejected response becomes consistent with the correct answer. Under the inhibitory account of negative priming, if the consequences of the regulation applied during the prime carry over to the probe, selecting the previously rejected response should take longer than selecting the same response after a neutral prime. The resulting incongruent-minus-neutral difference in probe RT constitutes the NP effect.

The inferential value of this paradigm lies in its control of the current probe. Because the probe and its correct response are held constant while the preceding prime condition is varied, the critical RT difference cannot be attributed solely to the difficulty of the current item. Instead, it indexes a carryover consequence of having rejected a misconception-consistent response on the preceding trial [31–33]. Within the inhibitory framework adopted in this study, NP is therefore treated as an inhibition-related carryover cost tied to prior conflict regulation. This task-specific interpretation allows the study to examine whether the inhibition-related carryover associated with prior conflict regulation varies with problem context and physics training.

If a less typical context increases the competition between misconception-consistent and normative responses, the regulation required on an incongruent prime trial should produce a larger subsequent NP cost. If physics training supports more robust problem representation and more fluent access to the normative relation, the contextual increase in this cost should be attenuated among physics majors. The NP paradigm thus links the theoretical account of context-sensitive inhibitory regulation to a specific, process-sensitive behavioral prediction.

D. The present study

Previous research has provided evidence that scientifically appropriate reasoning may require learners to regulate intuitive responses that remain cognitively available, and that the extent of this regulatory involvement may vary across scientific contents and levels of training [8–10,34]. A complementary line of research in physics education and transfer has shown that changes in problem representation can alter the accessibility of relevant knowledge, the recognition of underlying structure, and the likelihood of successful application [14,15,18,20–22]. These two lines of work have generally developed in parallel. Inhibitory-control research has primarily examined whether control is involved under particular conceptual conflicts, whereas research on problem representation has focused mainly on knowledge retrieval, reasoning performance, and transfer. It therefore remains unclear whether different representations of the same target conceptual conflict elicit different amounts of inhibitory-control mobilization and whether such contextual variation is moderated by physics training.

This study addressed this gap by integrating a contextual-accessibility account of physics reasoning with the inhibitory interpretation of negative priming. The design compared a prototypical horizontal context with a nonprototypical vertical context while preserving the target static-friction relation and the misconception-consistent response. It also compared novice high-school students with expert undergraduate physics majors. The negative-priming paradigm provided a process-sensitive means of estimating whether the regulation applied during an incongruent prime produced different subsequent carryover costs across contexts and groups. Within the inhibitory account adopted here, NP magnitude was interpreted as a behavioral index of the control mobilized during the preceding incongruent prime.

The central prediction was that contextual variation would change the magnitude of the NP effect and that this contextual modulation would differ by level of physics training.

H1: Problem context will moderate the negative-priming effect, such that NP will be larger in the non-prototypical context than in the prototypical context.

H2: Physics training will moderate the contextual change in NP, such that the nonprototypical-minus-prototypical increase in NP will be larger for novices than for experts.

III. METHOD

A. Participants

This study recruited 64 participants to form two groups representing distinct levels of expertise. The novice group consisted of 32 first-year high school students (17 male, 15 female). All novices had completed the curriculum unit on friction and possessed the basic knowledge required to distinguish between kinetic and static friction. This group was thus characterized by the absence of in-depth, professional physics schemas. The expert group comprised 32 undergraduate students (16 male, 16 female) majoring in physics. These students had been admitted through a selective process and had received systematic training in university-level mechanics, equipping them with the domain-specific knowledge structure necessary for handling complex physics conflict tasks. All participants were right-handed, native Chinese speakers with normal or corrected-to-normal vision, and reported no history of neurological or psychiatric disorders. Participation was voluntary, following the provision of informed consent.

To ensure that all participants possessed a correct understanding of the static friction concept, a screening procedure was implemented after the practice phase. Participants were required to verbally articulate the logical reasoning for determining the magnitude of static friction. Only those who could accurately identify and describe the relevant scientific concept were permitted to proceed to the main experiment. This screening procedure reduced the likelihood that subsequent performance differences were attributable to a complete lack of the target static-friction relation.

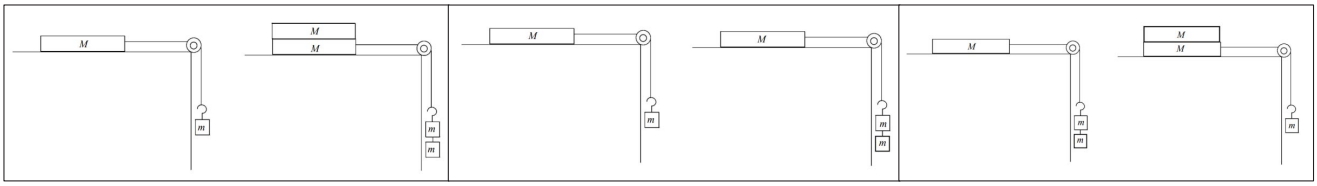
A priori sample-size planning was aligned with the primary trial-level inference. Our focal inferential target was the three-way interaction in probe-phase log response times (logRT), *Group* × *Context* × *Prime Type*, where *Prime Type* was operationalized via the NP contrast (incongruent-prime vs neutral-prime) using appropriate contrast coding. This effect was tested with a linear mixed-effects model including a random intercept for participant and, when supported by model convergence and identifiable variance components, a by-participant random slope for the *Prime Type* contrast. Each participant completed 96 prime-probe trials (48 per context). The critical NP effect was defined within each context on congruent-probe trials as the difference between the incongruent-prime and neutral-prime conditions, with 12 trials per cell in each context. Because no general closed-form solution exists for statistical power in this mixed-effects design, we conducted a Monte Carlo simulation-based power analysis to determine the required sample size. The simulation mirrored the planned model specification and trial counts, and power was evaluated for detecting the focal three-way interaction. Statistical significance was determined via a two-sided likelihood-ratio test comparing nested models with vs without the three-way interaction at $\alpha = 0.05$ (with $n_{\mathrm{sim}} = 2000$ simulation runs). We specified the smallest effect size of interest for the between-group difference in contextual modulation as $\Delta \log = 0.06$, corresponding to an approximate 6% multiplicative change in RT on the original scale. Under conservative assumptions for the residual and random-effects variance components—chosen to induce larger within- and between-participant variability on the logRT scale than would be expected under typical conditions and thus to yield a lower-bound estimate of power—the Monte Carlo simulations indicated that 30 participants per group would provide at least 0.80 power at $\alpha = 0.05$ to detect the focal three-way interaction.

B. Experimental materials

Two sets of static friction experimental items, based on a negative priming paradigm, were meticulously designed for this study, corresponding to the horizontal (prototypical) and vertical (nonprototypical) contexts, respectively. Each set comprised three types of items: incongruent, congruent, and neutral.

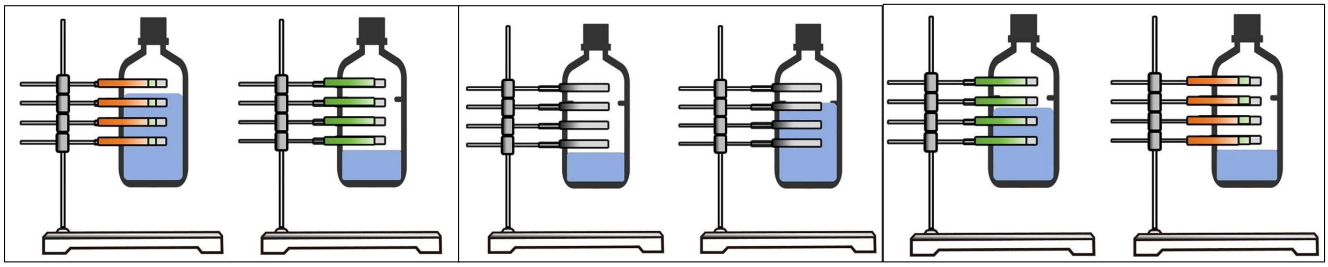
Each item consisted of two physical schematic diagrams presented side-by-side, positioned 160 pixels to the left and right of the screen center. The first set of tasks focused on static friction judgment in the horizontal context (see Fig. 1). The variation in normal force on the bottommost block was represented by stacking a differing number of blocks, while the magnitude of the the rope tension is mobilized by changing the number of weights. In the incongruent items, the design featured a larger normal force paired with a smaller tension (counterintuitive). The congruent items featured covarying changes in normal force and tension, while the neutral items maintained a constant normal force. Incongruent items paired a larger normal force with a smaller required static-friction force, thereby creating conflict between the misconception-consistent response and the normative response.

The tasks in the second group shifted to a vertical configuration, requiring participants to determine the static friction acting on a clamped bottle (see Fig. 2). To manipulate the normal force in this setup, the bottle was secured using clamps: the normal force was increased or decreased by varying the number of clamps. The contact area between the bottle and the clamps was consistently maintained, thereby deliberately avoiding the common misconception that "greater contact area leads to greater



(a) **Congruent** (b) **Neutral** (c) **Incongruent**

FIG. 1. An example of an experimental item under the horizontal (prototypical) condition is presented. In this setup, the normal force acting on the bottommost block was varied by changing the number of blocks stacked above it, while the static friction between the bottommost block and the table surface was manipulated by altering the number of weights applied. The figure illustrates three types of conditions: (a) congruent item, where a larger normal force is paired with a greater static friction force; (b) neutral item, where the normal force remains identical while the static friction force differs; (c) incongruent item, where a larger normal force is associated with a smaller static friction force, thereby eliciting an intuitive conflict.



(a) **Congruent** (b) **Neutral** (c) **Incongruent**

FIG. 2. An example of an experimental item under the vertical (nonprototypical) condition is presented. In this setup, the normal force acting on the bottle was manipulated by varying the number of clamps securing it, while the static friction between the bottle and the clamps was controlled by adjusting the mass of water inside the bottle. The figure illustrates three types of conditions: (a) congruent item, in which a larger normal force is paired with a greater static friction force; (b) neutral item, where the normal force is held constant while the static friction force differs; (c) incongruent item, where a larger normal force corresponds to a smaller static friction force, thereby eliciting an intuitive conflict.

friction [27].” In the figure, the normal force was symbolically represented by the number of clamps: four gray clamps corresponded to a smaller normal force; four gray plus four green clamps represented a medium normal force; and four gray, four green, plus four orange clamps produced a larger normal force; meanwhile, the weight of the bottle and the water contributed to the gravitational force that needed to be overcome. Incongruent trials were designed such that “greater normal force (more clamps)” was paired with “lighter bottle and water weight.” The spatial orientation shifted from the typical horizontal plane to a nonprototypical plane, altering the surface features and perceptual cues of the problem while preserving the underlying physical principles. This design allowed us to examine whether negative-priming carryover varied with contextual typicality and physics training.

To ensure both the scientific validity of the materials and the effectiveness of the representational-typicality manipulation, we conducted an expert and user review involving six university physics majors, six high-school students, and two experienced physics teachers. Reviewers evaluated the materials not only for content validity (scientific correctness, clarity, and alignment with the target concept of static friction), but also for whether the two spatial configurations differed in perceived prototypicality and everyday familiarity. The review confirmed that the materials were capable of accurately eliciting and assessing participants’ understanding of static friction. Importantly, reviewers consistently judged the horizontal configuration as the more typical and familiar representation, whereas the vertical configuration was perceived as less typical and comparatively unfamiliar, likely requiring additional mental reconstruction. This qualitative assessment provided an *a priori* basis for treating Context (horizontal vs vertical) as an operationalization of representational typicality, which was subsequently examined empirically via the neutral-probe RT comparison reported in the Results section.

Based on these items, four trial conditions were designed for each task set, resulting in a total of 96 prime-probe trial pairs. As shown in Table I, to precisely isolate the inhibitory cost and conceal the experimental aims, the design included not only the control condition (neutral-prime and congruent-probe) and the test condition (incongruent-prime and congruent-probe) but also specific filler conditions (featuring incongruent probes).

TABLE I. Design of prime-probe trial sequences in the negative priming paradigm.

Condition	Prime type	Probe type	Number of trials
Control trial	Neutral	Congruent	12
Test trial	Incongruent	Congruent	12
Filler trial	Neutral	Incongruent	12
	Incongruent	Incongruent	12

C. Procedure

All tasks were administered individually in a quiet laboratory environment on a 15.6-in. laptop computer using E-Prime 3.0, and both RTs and accuracy (ACC) were recorded with millisecond precision. Participants completed sequences of paired prime-probe trials in two spatial contexts (horizontal and vertical), with each trial categorized as a control, test, or filler trial. In control trials, a neutral prime preceded a congruent probe to establish a baseline response, whereas in test trials, an incongruent prime was presented to activate the misconception that "static friction magnitude is determined by normal force," followed by a congruent (misconception-consistent) probe that served as a diagnostic item. Slower responding to a congruent probe following an incongruent prime, relative to the neutral-prime baseline, constituted the negative-priming effect. Under the inhibitory account adopted in this study, this difference was interpreted as an inhibition-related carryover cost. Filler trials, which included incongruent probes, were interspersed throughout the session to conceal the experimental aims and prevent participants from developing anticipatory response strategies.

Prior to the formal experiment, participants received detailed instructions emphasizing the importance of both speed and accuracy, followed by four practice prime-probe pairs to ensure familiarity with the task. The experimental flow is shown in Figs. 3 and 4. Each trial began with a 500 ms central fixation cross, after which the prime stimulus was displayed until the participant responded, with a maximum duration of 3000 ms. A second fixation cross appeared for 500 ms to recenter attention before the probe stimulus was presented under the same timing constraints. Upon responding to the probe, a 3000 ms visual noise mask was displayed to eliminate any after-images from the preceding stimuli and to ensure perceptual independence across trials. Participants responded using the left index finger for the "F" key and the right index finger for the "J" key, corresponding to the left and right schematics, respectively; this mapping was kept consistent within participants, while the side of the correct response was counterbalanced across items to prevent lateral biases.

During the test phase, each participant completed a total of 96 prime-probe pairs, with 48 pairs presented in the horizontal context and 48 in the vertical context, ensuring an overall equal frequency of the two context types. To avoid confounding context with time-related factors such as practice or fatigue, and to control for sequential structure, all prime-probe pairs were presented in a pseudorandomized order, mixed within participants. This sequence was generated individually for each participant under the following constraints: (1) no two consecutive trials belonged to the same trial type; (2) left and right keypress responses were evenly distributed throughout the session; and (3) horizontal and vertical contexts were evenly distributed and numerically balanced across the entire session.

RTs and accuracy were recorded for all trials. RT was defined as the interval between the onset of the probe display and the keypress response. Trials with incorrect responses, omissions, or RTs shorter than 200 ms or longer than 3000 ms were flagged for exclusion. This presentation and filtering procedure maintained strict experimental

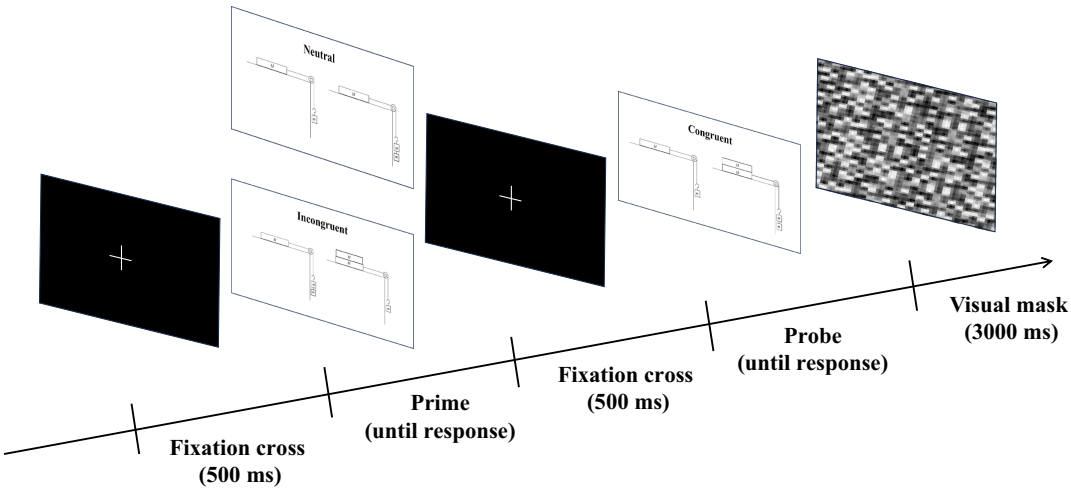


FIG. 3. Experimental procedure for the horizontal condition. The control condition involved a neutral prime followed by a congruent probe. The test condition consisted of an incongruent prime followed by a congruent probe.

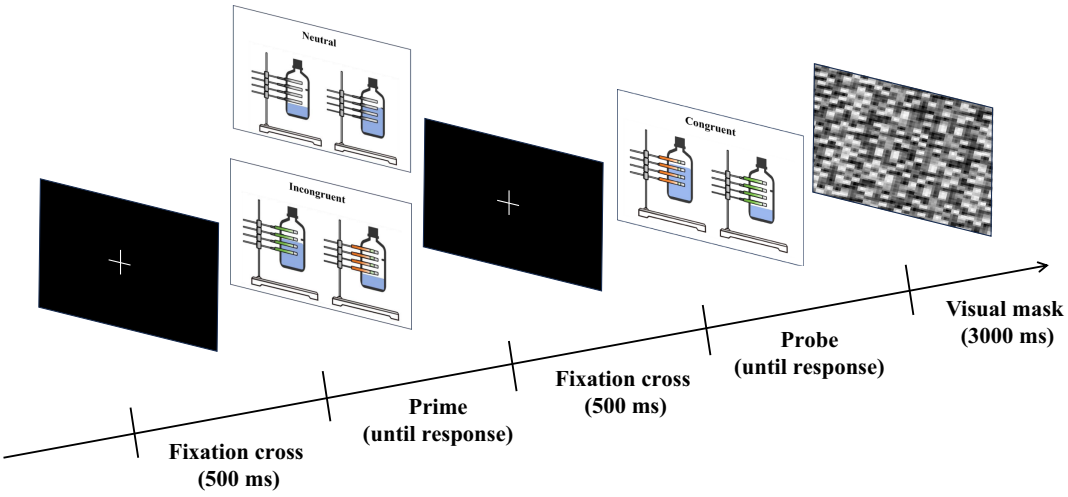


FIG. 4. Experimental procedure for the vertical condition. The control trial consisted of a neutral prime followed by a congruent probe. The test trial consisted of an incongruent prime followed by a congruent probe.

control and reproducibility while minimizing potential interference from order and timerelated factors on context comparisons, thereby providing a more reliable data foundation for subsequent analyses and for characterizing inhibitionrelated processing costs.

D. Data analysis

To test the research hypotheses and evaluate the predicted inhibition-related processing pattern, a multistage analysis was conducted, progressing from data preprocessing and descriptive checks to the primary analysis of the negative-priming effect.

1. Data preprocessing

Prior to formal analysis, raw behavioral data underwent a two-step preprocessing procedure to ensure data quality and validity. First, to guarantee that the measured RTs reflected meaningful cognitive processing rather than errors, only trials with correct responses in both the prime and probe phases were retained for subsequent RT analysis. Incorrect trials were excluded. Second, to minimize the influence of extreme values caused by lapses in attention or motor errors, RT outliers were identified and removed on a per-participant basis. Outliers were defined as RTs falling more than two standard deviations above or below the individual participant's mean RT for each experimental condition.

2. Analysis stages and rationale

Stage 1: Accuracy analysis. Accuracy was analyzed using a 2 (Group: Novice vs Expert) × 2 (Context: Prototypical vs Nonprototypical) mixed-factorial ANOVA. This analysis assessed whether accuracy differed by group or context and whether the RT results were accompanied by evidence of a speed-accuracy trade-off.

Stage 2: Analysis of context-related prime-phase processing. To assess whether prime-phase processing demands differed between the prototypical horizontal context and the nonprototypical vertical context, mean RTs on neutral-prime trials were compared using a 2 (Group: Novice vs Expert) × 2 (Context: Prototypical vs Nonprototypical) mixed-factorial ANOVA. Longer neutral-prime RTs in the vertical context were interpreted as being consistent with greater baseline processing demands associated with the nonprototypical representation.

Stage 3: Primary analysis of the negative-priming effect. The primary analysis tested whether inhibition-related carryover cost depended on problem context and physics training. Probe-phase RTs were log-transformed and analyzed at the trial level using a linear mixed-effects model with fixed effects of Group (Novice vs Expert), Context (Prototypical vs Nonprototypical), Prime Type (Neutral vs Incongruent), and all interactions:

$$\log(\mathrm{RT}) \sim \mathrm{Group} \times \mathrm{Context} \times \mathrm{PrimeType} + (1|\mathrm{Participant}).$$

A model including a by-participant random slope for Prime Type was also evaluated. Because this specification produced a singular fit, the random-intercept model was retained as the primary model.

Fixed effects were evaluated using Type III tests with Satterthwaite degrees of freedom as implemented in `lmerTest`. The *a priori* inferential focus was the Group × Context × Prime Type interaction. Within each Group × Context cell, NP was estimated as the planned contrast between the incongruent-prime and neutral-prime conditions on the logRT scale:

$$\Delta_{\log} = \widehat{\log(\mathrm{RT})}_{\mathrm{Incongruent}} - \widehat{\log(\mathrm{RT})}_{\mathrm{Neutral}}.$$

Contrasts were estimated using Kenward-Roger degrees of freedom as implemented in `emmeans` and were reported with standard errors, t statistics, p values, and 95% confidence intervals. Because these contrasts were specified *a priori*, unadjusted p values and 95% confidence intervals were reported.

For interpretation on the original RT scale, log-scale contrasts were exponentiated and reported as RT ratios, $\exp(\Delta_{\log})$, and percentage changes, $100[\exp(\Delta_{\log}) - 1]\%$. Model-estimated marginal means were back-transformed for visualization. Because the model was fitted to log-transformed RTs, these back-transformed estimates are geometric means rather than arithmetic means. The descriptive prime-phase table reports raw arithmetic means and standard deviations, whereas the probe-phase figure displays model-estimated marginal geometric means; the two displays therefore summarize different task phases and different estimands.

All fixed-effect coefficient estimates, standard errors, 95% confidence intervals, and inferential statistics were reported for the primary model. Model fit was summarized using marginal and conditional R^2.

IV. RESULTS

A. Accuracy analysis

A 2 (Group: Novice vs Expert) × 2 (Context: Prototypical vs Nonprototypical) mixed-factorial analysis of variance (ANOVA) was conducted on task accuracy. Accuracy exceeded 95% in all experimental conditions. The analysis revealed no significant main effects of Group or Context and no significant Group × Context interaction (all $ps > 0.05$). This uniformly high level of accuracy indicated that participants in both groups were generally able to apply the target static-friction relation and provided no evidence that the subsequent RT pattern was driven by a speed-accuracy trade-off.

B. Prime-phase processing analysis

To examine context-related differences in prime-phase processing, neutral-prime RTs were analyzed using a 2 (Group: Novice vs Expert) × 2 (Context: Prototypical vs Nonprototypical) mixed-factorial ANOVA. Descriptive statistics for all prime conditions are reported in Table II and displayed in Fig. 5.

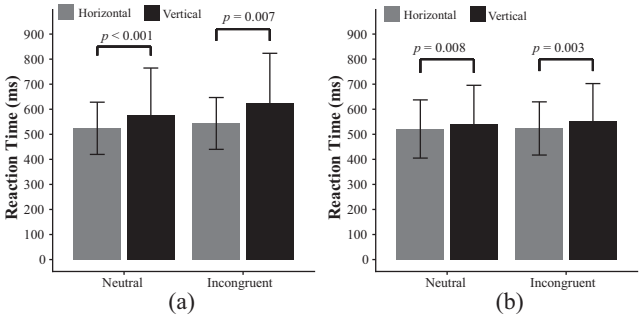


FIG. 5. Mean RTs for neutral and incongruent prime trials in the prototypical horizontal and nonprototypical vertical contexts, shown separately for the (a) novice and (b) expert groups.

The focal main effect of Context was significant, $F(1, 62) = 31.45$, $p < 0.001$, $\eta_p^2 = 0.34$, indicating that neutral-prime RTs were longer in the nonprototypical vertical context than in the prototypical horizontal context. For novices, mean neutral-prime RT increased from 523.92 ms in the prototypical context to 577.86 ms in the nonprototypical context. For experts, the corresponding means were 521.17 and 542.17 ms. This pattern was consistent with greater baseline processing demands in the nonprototypical representation.

Follow-up paired-samples t tests examined the context difference within each group. For neutral primes, RTs were significantly longer in the nonprototypical context for both novices, with an increase of 53.94 ms, $t(31) = 4.67$, $p < 0.001$, and experts, with an increase of 21.00 ms, $t(31) = 2.85$, $p = 0.008$.

A context-related increase was also observed for incongruent primes. Among novices, mean incongruent-prime RT increased from 543.33 ms in the prototypical context to 624.42 ms in the nonprototypical context, an increase of 81.09 ms, $t(31) = 2.89$, $p = 0.007$. Among experts, mean RT increased from 523.33 to 574.71 ms, an increase of 51.38 ms, $t(31) = 3.24$, $p = 0.003$. Taken together, the prime-phase results showed longer processing times in the nonprototypical vertical context than in the prototypical horizontal context.

TABLE II. Descriptive statistics for observed prime-phase reaction times in the novice and expert groups across the prototypical horizontal and nonprototypical vertical contexts. Values are raw arithmetic means in milliseconds, with standard deviations in parentheses.

	Horizontal (prototypical)		Vertical (nonprototypical)	
Group	Neutral	Incongruent	Neutral	Incongruent
Novice	523.92 (104.24)	543.33 (103.40)	577.86 (186.61)	624.42 (198.88)
Expert	521.17 (116.15)	523.33 (106.14)	542.17 (153.37)	574.71 (151.26)

TABLE III. Fixed-effect estimates from the linear mixed-effects model of probe-phase log-transformed reaction times.

Effect	Estimate	SE	95% CI	df	t	p
Intercept	6.3707	0.0051	[6.3606, 6.3807]	3067	1246.03	< 0.001
Group	0.1262	0.0102	[0.1061, 0.1462]	3067	12.34	< 0.001
Context	0.1571	0.0102	[0.1371, 0.1772]	3067	15.36	< 0.001
Prime Type	0.0689	0.0102	[0.0489, 0.0890]	3067	6.74	< 0.001
Group × Context	−0.0345	0.0205	[−0.0746, 0.0056]	3067	−1.69	0.092
Group × Prime Type	0.0756	0.0205	[0.0355, 0.1157]	3067	3.69	< 0.001
Context × Prime Type	0.1059	0.0205	[0.0658, 0.1460]	3067	5.18	< 0.001
Group × Context × Prime Type	0.1164	0.0409	[0.0362, 0.1966]	3067	2.85	0.004

Note. The dependent variable was the natural logarithm of probe reaction time. Group was effect-coded as −0.5 for experts and +0.5 for novices. Context was effect-coded as −0.5 for the prototypical horizontal condition and +0.5 for the nonprototypical vertical condition. Prime Type was effect-coded as −0.5 for neutral primes and +0.5 for incongruent primes. CI denotes confidence interval.

C. Mixed-effects analysis of probe-phase negative priming

Probe-phase reaction times were analyzed on the log-transformed scale, log(RT), using a linear mixed-effects model fitted to trial-level data. The model included fixed effects of Group (Novice vs Expert), Context (Prototypical vs Nonprototypical), Prime Type (Neutral vs Incongruent), and all interactions, with participant included as a random intercept. Fixed effects were evaluated using Type III tests with Satterthwaite degrees of freedom. The corresponding fixed-effect coefficient estimates and 95% confidence intervals are reported in Table III.

The model revealed significant main effects of Group, $F(1, 3067) = 152.67$, $p < 0.001$, Context, $F(1, 3067) = 236.67$, $p < 0.001$, and Prime Type, $F(1, 3067) = 45.55$, $p < 0.001$. The Group × Prime Type interaction was significant, $F(1, 3067) = 13.69$, $p < 0.001$, as was the Context × Prime Type interaction, $F(1, 3067) = 26.87$, $p < 0.001$. The Group × Context interaction was not significant, $F(1, 3067) = 2.85$, $p = 0.092$.

The significant Context × Prime Type interaction indicated that, averaged across groups, the negative-priming effect was larger in the nonprototypical context than in the prototypical context, supporting H1. Critically, these effects were qualified by a significant Group × Context × Prime Type interaction, $F(1, 3067) = 8.12$, $p = 0.0044$, indicating that the contextual change in negative priming differed between the novice and expert groups. This result supported H2. The model yielded a marginal R^2 of 0.137 and a conditional R^2 of 0.17.

Planned contrasts were used to estimate negative priming within each Group × Context cell as the difference between probe RTs following incongruent and neutral primes (Incongruent-Neutral) on the logRT scale. Contrast estimates are reported in Table IV.

In the prototypical context, NP was small and was not statistically significant for either novices, $\Delta_{\log} = 0.0247$, $t(3013.40) = 1.20$, $p = 0.229$, 95% CI $[-0.0155, 0.0649]$, or experts, $\Delta_{\log} = 0.0073$, $t(3012.70) = 0.36$, $p = 0.721$, 95% CI $[-0.0328, 0.0474]$.

In contrast, a significant positive NP effect was observed in the nonprototypical context for both groups. The effect was larger for novices, $\Delta_{\log} = 0.1887$, $t(3012.70) = 9.24$, $p < 0.001$, 95% CI $[0.1487, 0.2288]$, than for experts, $\Delta_{\log} = 0.0550$, $t(3012.70) = 2.69$, $p = 0.007$, 95% CI $[0.0149, 0.0950]$. After back-transformation, NP in the nonprototypical context corresponded to an approximately 20.77% increase in RT for novices and a 5.65% increase for experts. Consistent with the significant three-way interaction, the increase in NP from the prototypical to the nonprototypical context was larger for novices than for experts.

Figure 6 presents the model-estimated interaction pattern on the original millisecond scale. Because the model was fitted to log-transformed RTs, the estimated marginal means and their confidence limits were exponentiated;

TABLE IV. Planned NP contrasts on probe-phase reaction times from the trial-level linear mixed-effects model. NP was defined as the within-cell difference *Incongruent-Neutral* on the logRT scale. Degrees of freedom were calculated using the Kenward-Roger approximation. Back-transformed effects are reported as percentage changes in RT.

Group	Context	$\Delta_{\log}$	SE	df	t	p	95% CI for $\Delta_{\log}$	% change in RT (95% CI)
Novice	Prototypical	0.0247	0.0205	3013.40	1.20	0.229	$[-0.0155, 0.0649]$	+2.50%[−1.54%, 6.70%]
Expert	Prototypical	0.0073	0.0204	3012.70	0.36	0.721	$[-0.0328, 0.0474]$	+0.73%[−3.22%, 4.85%]
Novice	Nonprototypical	0.1887	0.0204	3012.70	9.24	<0.001	$[0.1487, 0.2288]$	+20.77%[16.03%, 25.71%]
Expert	Nonprototypical	0.0550	0.0204	3012.70	2.69	0.007	$[0.0149, 0.0950]$	+5.65%[1.50%, 9.97%]

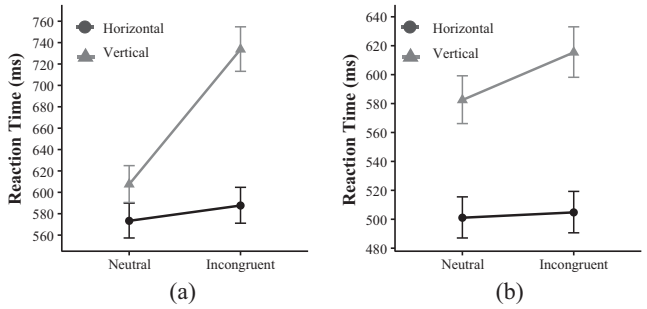


FIG. 6. Model-estimated marginal means for probe-phase reaction times as a function of Prime Type and Context, shown separately for the (a) novice and (b) expert groups. The mixed-effects model was fitted to trial-level log-transformed RTs. Estimated marginal means and their 95% confidence limits were exponentiated for presentation on the original millisecond scale; the plotted values are therefore geometric means rather than raw arithmetic means.

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V. DISCUSSION

The present study examined whether the inhibitory-control mobilization associated with the same physical relation varies across representational contexts and whether this contextual modulation differs as a function of physics training. In the prototypical context, negative-priming effects were small and not statistically reliable for either novices or experts. In the nonprototypical context, reliable negative-priming effects emerged in both groups and were substantially larger among novices than experts. Within the inhibitory account adopted here, this pattern is consistent with a task-sensitive view of control mobilization, whereby inhibitory demand is shaped by the competition generated under particular task conditions rather than by the target misconception alone [34,47,52]. Representational context may alter the relative accessibility of normative and misconception-consistent responses, thereby changing the strength of their competition and the control required to resolve it [11–15,20]. Physics training may attenuate this contextual amplification by supporting more structured knowledge representations and more stable access to the underlying physical relation across surface variations [15,18,21,22]. Taken together, the findings specify how problem representation and domain knowledge jointly shape inhibitory regulation during conceptual conflict.

A. Representational context reshapes conceptual competition and inhibitory-control mobilization

The context-dependent negative-priming pattern indicates that the inhibition-related processing associated with the same conceptual conflict varies across problem representations. Within the inhibitory account adopted here, this variation may arise because representational context reorganizes the relative accessibility of the normative and misconception-consistent responses. Contextual cues can shape which knowledge becomes accessible and how rapidly it enters the response-selection process [14,15,20]. Changes in relative accessibility may, in turn, determine whether the misconception-consistent response becomes a consequential competitor and how strongly control must be mobilized for the normative response to govern judgment [34,47].

This interpretation connects directly with research on problem representation, transfer, and cognitive accessibility in physics education. Prior work has shown that surface features influence not only whether learners recognize a problem's underlying relational structure, but also whether relevant knowledge is retrieved when it is needed [17–23]. When contextual cues are strongly linked to an existing knowledge structure, the normative physical relation can become available rapidly enough to gain an advantage in response selection. When representational change weakens established cue-relation mappings, access to that relation may become less fluent, allowing the misconception-consistent response to gain relative accessibility [11–15]. Representational context therefore shapes not only what knowledge is retrieved, but also the relative strength with which competing responses enter the selection process.

From an inhibitory perspective, control is mobilized within this competition structure. When the normative response has a clear processing advantage, a misconception-consistent response may remain cognitively available without exerting sufficient influence to disrupt response selection. As its relative accessibility increases, competition intensifies, and selecting the normative response may require stronger or more sustained regulation [34,46,47,52]. Representational differences therefore translate into differences in inhibitory demand: representation does not determine control directly, but alters the conflict that control must resolve by changing the relative accessibility of competing responses.

This mechanism also clarifies the context sensitivity of conceptual coexistence. Conceptual-coexistence accounts propose that misconception-consistent knowledge may remain cognitively available after normative scientific knowledge has been acquired [3,5]. Behavioral and neurocognitive evidence further indicates that intuitive knowledge can remain active even among scientifically trained individuals [4,6,7]. Continued availability, however, does not imply a constant degree of interference. Whether a misconception-consistent response requires substantial inhibition depends on whether a particular representation gives it sufficient competitive strength to influence response selection. Conceptual coexistence therefore refers to the potential availability of competing knowledge,

whereas inhibition-related processing reflects the extent to which that potential competition is realized under specific task conditions.

B. Physics training attenuates the contextual amplification of inhibitory demand

The contextual increase in negative priming was significantly smaller for experts than for novices, suggesting that the expert advantage primarily reflected reduced sensitivity to representational change rather than a uniform inhibitory advantage across contexts. In other words, the groups differed less in whether they experienced conceptual conflict than in the extent to which the nonprototypical representation amplified that conflict.

This pattern can be explained in terms of domain-knowledge organization. Experts tend to represent physics problems in terms of underlying principles and relational structures, whereas novices are more likely to rely on familiar objects, spatial orientations, and other surface features [18,21,22]. Knowledge organized around underlying relations supports recognition and retrieval of those relations across variations in surface form [16,17,19,20]. The normative physical relation may therefore remain relatively accessible to experts when the representation changes, limiting the loss of its processing advantage. Within the inhibitory account adopted here, more stable access to the normative relation leaves less opportunity for the misconception-consistent response to become strongly competitive and consequently reduces the control required to maintain normative responding. By contrast, novices' access to the normative relation may depend more heavily on prototypical cues. When those cues change, the normative response may lose relative accessibility, allowing the misconception-consistent response to exert greater influence and increasing the resulting inhibition-related cost [14,15].

This interpretation extends existing accounts of expert advantage by locating part of that advantage in the conditions that give rise to control demand. Expert performance need not reflect only stronger or more efficient regulation after conflict has emerged. Physics training may also reduce the need for regulation by stabilizing access to normative relations across representations and thereby limiting the competition elicited by contextual change. Domain-knowledge organization and cognitive control are therefore functionally interdependent: knowledge organization shapes the competition on which control must operate, whereas control becomes consequential when that competition is strong enough to influence response selection.

C. Alternative mechanisms and theoretical discrimination

Negative priming is not a process-specific measure of inhibition [32,33]. Although the present study adopted an *a priori* inhibitory account and interpreted delayed probe responses following incongruent primes as a carryover cost of prior conflict regulation, similar behavioral patterns may arise from episodic retrieval, stimulus-response binding and retrieval, selective-attention processes, or temporal discrimination at the probe stage [53–57]. These accounts differ primarily in whether the negative-priming cost originates from regulation of a competing response during the prime or from the retrieval and reconfiguration of prior stimulus, response, and selection states during the probe. Relative-processing-time and parallel-processing perspectives address an earlier component of the same sequence: how the relative speed and strength with which normative and misconception-consistent responses become available shape subsequent response selection [11–15]. The present findings therefore support a processing pattern consistent with inhibition, but do not establish persistent inhibition as the sole source of the negative-priming effect.

The findings nevertheless impose a common explanatory requirement on these accounts. The critical pattern is not simply slower responding in the nonprototypical context, but an increase in the prime-related carryover cost calculated relative to the neutral-prime baseline within each context, together with a smaller contextual increase among experts. Because the current probe and its required response were functionally held constant while prime history varied, this pattern cannot be attributed solely to the difficulty of the probe itself. Any adequate account must therefore explain how problem representation and physics training alter a cross-trial influence of the preceding selection episode.

Under the inhibitory account, the nonprototypical representation may have reduced the relative accessibility of the normative physical relation, allowing the misconception-consistent response to become more competitive and increasing the control mobilized during the prime. More stable cue-relation mappings among more highly trained participants may have limited this increase in competition and its subsequent carryover. This interpretation corresponds directly to the study's *a priori* hypotheses and task structure, but it does not exclude probe-stage mechanisms. Episodic-retrieval and binding-retrieval accounts could also accommodate the pattern if representational context systematically altered event encoding, feature retrieval, or conflict between the current response requirement and the prior selection episode—and if this alteration was weaker among experts [53–56]. Selective-attention and temporal-discrimination accounts would similarly need to specify how representational typicality and training jointly affected attentional carryover or the discrimination of successive processing episodes [33,57].

These mechanisms need not be mutually exclusive. Conceptual competition may first recruit control during the prime; the resulting stimulus, response, and selection states may then be encoded as an event representation and retrieved during the probe. The observed cost may

therefore reflect both prime-stage competition and regulation and probe-stage retrieval and response reconfiguration, with their relative contributions depending on task structure [32,33]. Relative-processing-time accounts describe an earlier link in this sequence: if a nonprototypical representation delays access to the normative relation, the misconception-consistent response may retain a processing advantage for longer, increasing the likelihood of consequential competition [14,15]. The theories thus compete over which processes are necessary and how much each contributes to the contextual and training-related modulation of negative priming, rather than over whether the proposed processes can coexist.

Future studies should use theoretically diagnostic manipulations to separate these possibilities. Conceptual-response status, stimulus identity or perceptual-feature repetition, and motor-response repetition could be varied orthogonally. A probe cost that continues to depend on whether the conceptual response was previously rejected despite changes in stimulus appearance and response key would provide stronger support for concept-level inhibition. By contrast, an effect governed primarily by complete or partial repetition of specific stimulus-response features would favor episodic-retrieval or binding-retrieval accounts [53,55,56]. Manipulating the prime-probe interval and its temporal predictability could distinguish the persistence and decay of prior control from changes in temporal discrimination. Manipulations of stimulus duration, response deadlines, or prior activation of the normative relation could further test whether representational context acts by altering the relative activation trajectories of the competing responses.

Time-sensitive measures such as eye tracking and electroencephalography could help determine whether contextual and group differences first emerge during representational construction, conflict monitoring, response selection, or probe-stage retrieval. In future designs that produce sufficient variation in both accuracy and response time, joint modeling could further test whether context and training primarily affect evidence-accumulation rate, response threshold, or nondecision processes [48,49]. Such models provide a formal localization of latent processing components rather than an independent mechanism of negative priming; their theoretical value therefore depends on their integration with experimentally diagnostic manipulations.

D. Limitations and future directions

Several limitations define the scope of the present conclusions. First, contextual typicality was instantiated through a contrast between two specific item sets. Although both sets represented the same target relation in static friction, they also differed in their objects, visual features, and representation of the relevant forces. The observed contextual effect therefore cannot be attributed exclusively to typicality. Future studies should manipulate representational typicality while more tightly controlling visual complexity, object identity, and response mappings. Second, the present study relied on negative priming as its primary process measure. This design provided evidence that the carryover from a preceding conflict episode varied with representational context, but it did not uniquely identify the cognitive mechanism underlying that carryover. Combining negative priming with experimentally controlled manipulations of stimulus and response repetition, eye tracking, or temporally sensitive neurocognitive measures could help determine whether the effect arises primarily during representational processing, conflict regulation, response selection, or retrieval at the probe stage. Third, the novice and expert groups differed not only in physics training but also in age, educational experience, and selection history. The observed group difference therefore cannot be attributed solely to physics training. Longitudinal studies and training interventions would provide a stronger test of whether increasingly extensive and varied experience with physics directly stabilizes access to normative relations across representational contexts.

VI. CONCLUSION

Using a NP paradigm, this study examined whether contextual typicality modulates task-evoked inhibitory-control mobilization during static-friction reasoning, and whether this modulation differs with physics training. Within the inhibitory account adopted here, NP magnitude was treated as a behavioral index of the control mobilized during the preceding incongruent prime. The results yield two main conclusions. First, inhibitory-control mobilization was strongly context-dependent. NP was negligible in the prototypical horizontal context for both groups but emerged reliably in the nonprototypical vertical context. On the original RT scale, the vertical-context NP corresponded to an approximate 20.77% increase for high-school students and a 5.65% increase for undergraduate physics majors. Second, physics training moderated this contextual pattern. Physics majors showed substantially smaller NP than high-school students in the vertical context, although the effect remained statistically reliable.

These findings advance process-based accounts of conceptual conflict by showing that the inhibitory control mobilized to overcome a misconception-consistent response is not fixed across representations of the same physical relation. Contextual typicality shapes the relative accessibility and competition of normative and misconception-consistent responses, whereas physics training reduces the extent to which a nonprototypical representation amplifies the resulting control requirement. For physics education, the findings support instructional and assessment practices that extend beyond canonical prototypes. Systematic engagement with structurally equivalent but contextually varied problems may strengthen access to invariant physical relations and promote more stable

conceptual performance across representations. Future research should examine a broader range of contextual-typicality manipulations and integrate complementary process measures, such as eye tracking, neurocognitive indices, and joint modeling of accuracy and response time, to specify more precisely how contextual representation and physics training shape conceptual competition and inhibitory-control mobilization.

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DATA AVAILABILITY

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

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